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LEONID MIKHAILOVSKY

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ABSTRACT

This study presents an evaluation of an existing concrete bridge through non-destructive concrete tests in-situ, correlated with tests on concrete cores as well as through the in-situ data on its structural dimensions. Regression analyses of data are performed and based on the developed calibration curves for non-destructive tests several sets of the values of concrete strength are estimated for a field of test points. A statistical evaluation of the results is used in order to select the best non-destructive test method of testing concrete. Based on the established relationships between the concrete strength and non-destructive tests recommendations are made towards the improvement of existing evaluation techniques.

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LIST OF SYMBOLS

A_o = empirical constant

A_1 = empirical constant

A_2 = empirical constant

a = empirical constant

B = empirical constant

b = empirical constant

d = measured difference between concrete thickness and the reference distance of the rigid caliper

D = core diameter

e = base of natural logarithm

E = Young's modulus of elasticity

f'_c = compression strength of concrete

f'_e = estimated compression strength of concrete

h_s = specified height of girder stem

h = mean of measured heights of girder stem

ℓ = pulse velocity path length in-situ

ℓ_1 = stem thickness by rigid caliper

ℓ_2 = stem thickness from cores

L_H = core length with both ends rough

L_i = core length with a rough and a smooth end

L_j = core length with both ends smooth

L_S = specified girder span

L_M = measured girder span

m = number of degrees of freedom

n = number of observations

n^* = number of observations plus 2

r = coefficient of correlation

R = rebound number

R_{max} = maximum rebound number

R_{mean} = mean rebound number

R_{min} = minimum rebound number

$\bar{R}^*$ = mean value of strength

R^* = specified value of strength

t_H = propagation time of the ultrasonic pulse in the core with both ends rough

t_i = propagation time of the ultrasonic pulse in the core with a rough and a smooth end

t_j = propagation time of the ultrasonic pulse in the core with both ends smooth

$t_{\alpha,m}$ = random variable of Student's t distribution

$\bar{U}$ = mean value of applied load

U = specified value of applied load

v = coefficient of variation

V = pulse velocity in concrete

V_H = pulse velocity in the core with both ends rough

V_i = pulse velocity in the core with a rough and a smooth end

V_j = pulse velocity in the core with both ends smooth

V_p = pulse velocity in concrete paste

V_R = coefficient of variation of strength

V_u = coefficient of variation of load

W = weight of specimen

X = independent variable

$\bar{X}$ = sample mean

Y = dependent variable

$\bar{\alpha}$ = separation function

α = confidence limit

β = safety index

δ = correction factor between pulse velocities measured in-situ and in cores

Δt = propagation time losses in pulse velocity tests due to roughness on two surfaces

Δ_v = increase in pulse velocity due to absence of transverse 13 mm ϕ steel bars in concrete

Δ'_{NDT} = error of non-destructive method value in comparison with results on 31 cores

λ_j = size of simulated group

μ = population mean

μ' = lower limit value of population mean

μ'' = upper limit value of population mean

μ_{NDT} = population mean of non-destructive test results

μ'_{NDT} = lower limit value of population mean of non-destructive test results

μ''_{NDT} = upper limit value of population mean of non-destructive test results

μ_x = population mean of pulse velocities

μ'_x = lower limit population mean of pulse velocities

σ = population standard deviation

σ' = lower limit value of σ

σ'' = upper limit value of σ

$\hat{\sigma}$ = sample standard deviation

$\hat{\sigma}_e$ = sample standard deviation of estimated concrete strength

$\hat{\sigma}_t$ = sample standard error of the test method for given number of observations

$\hat{\sigma}_t^s$ = sample standard error of the test method for required number of observations

σ_x = population standard deviation of pulse velocities

σ_x'' = upper limit population standard deviation of pulse velocities

1. INTRODUCTION

1.1 General

In 1980 the CSA Technical Committee on Highway Bridges introduced Clause 12 to CAN3-S6, as a new concept to be used parallel with existing bridge rating systems. This concept "provides a method whereby the strength of a bridge is determined on a statistical basis and compared to the effects of any desired load"(14).

The basis of a probabilistic approach in evaluation of structures are described by MacGregor in (19). The basic equation is:

$$\bar{R}^* \left[e^{-\beta\bar{\alpha}V_R}\right] > \bar{U}\left[e^{\beta\bar{\alpha}V_u}\right] \qquad (1.1)$$

where $\bar{R}^*$ = mean value of strength;

$\bar{U}$ = mean value of applied load;

V_R = coefficient of variation of strength;

V_u = coefficient of variation of load;

$\bar{\alpha}$ = separation function = 0.75

β = safety index

The difference between the evaluation of an existing structure and the design of a new one is that in the latter case, the mean value of strength $\bar{R}^*$ and the mean value of applied load $\bar{U}$ are unknown and replaced by specified values R and U through the relationships $\bar{R}^* = R^*\gamma_R$ and $\bar{U} = U\gamma_U$,

where γ_R and γ_U are specified factors based on previous studies and experience.

The evaluation of an existing structure provides an opportunity of evaluating the actual values $\bar{R}^*$ and $\bar{U}$ and corresponding coefficients of variation V_R and V_U.

The present investigation is directed toward finding practical ways of evaluation of the values $\bar{R}^*$ and V_R. As shown by Scanlon (25) involvement of actual values of concrete strength and structural dimensions can be of a significant benefit in the asessment of reliability of an existing structure, particularly when shear strength or axial compression is critical.

1.2 Problem Statement

So far there is no satifactory procedure that would provide the necessary parameters for a concrete strength evaluation without damaging structural elements, despite the fact that a number of non-destructive test methods are now available. To achieve this goal an extensive research is necessary to correlate the data from non-destructive methods with results of recognized destructive techniques.

Recent developments in this area have taken the approach of employing different combinations of non-destructive methods in order to improve the correlation between the predicted strength and strength obtained by loading of concrete cylinders or drilled concrete cores.

Due to the fact that most researchers deal primarily

with concrete cast in laboratories, application of formulas resulting from these correlations to structural concretes may not be appropriate. This is particularly the case when the correlations require a knowledge of the composition of the concrete, which in a great majority of cases is not available for existing structures.

1.3 Objectives and Scope

The main objectives of the study can be summarized as follows:

1. To assess the dimensional variations in an existing bridge superstructure.
2. To evaluate the effectiveness of the ultrasonic pulse velocity method in evaluation of concrete strength in an existing bridge structure.
3. To evaluate the effectiveness of the rebound number method in evaluation of concrete strength in an existing bridge structure.
4. To evaluate the combined method of concrete testing, i.e. involving pulse velocities and rebound numbers.
5. To evaluate the relationship between pulse velocities in-situ and in cores.
6. To develop a procedure for selection of core locations based on pulse velocities data on concrete in-situ.
7. To develop correlation curves between non-destructive test data and compressive strength of cores.

The scope of this study consisted of the following:

1. Review of drawings and specifications used for the construction of the bridge under investigation.
2. Development of a procedure for field measurements of bridge dimensions.
3. Development of a procedure for non-destructive testing of a bridge superstructure.
4. Obtaining of cores at random locations of the structure.
5. Statistical evaluation of the geometry of the bridge superstructure.
6. Development of correlation formulas for non-destructive test data vs. concrete strength.
7. Comparison of the concrete strength obtained from different correlation formulas using non-destructive test results in-situ with the results of compressive tests of cores and specified values of concrete strength for this structure.

2. NON-DESTRUCTIVE TEST METHODS AND CORING

2.1 Introduction

Nondestructive test methods that have been developed to evaluate concrete quality include the rebound method, sonic and ultrasonic testing, penetration techniques, radiographic, nuclear, and electrical methods, acoustic emission, and pull-out tests. These methods have been described by Malhotra.(20) They provide information on various aspects of concrete quality. However none of these methods measures compressive strength directly. To assess the concrete strength it is necessary to calibrate the nondestructive test results against direct strength measurements obtained from cylinder tests, or in the case of existing structures, from tests on drilled cores.

In the present study, two methods, ultrasonic pulse velocity and rebound hammer, were applied to evaluate concrete in an existing bridge structure. Concrete cores were also obtained and tested in compression. In this chapter the selected nondestructive test methods are reviewed as well as the procedures for drilling and testing concrete cores.

2.2 Sonic Tests

These tests usually involve determination of the resonant frequency of a specimen as described by Whitehurst (34).

Equipment used to perform these tests varies from the hammer and home-made sonometer to electronic signal generators for driving the specimen and sophisticated electronic counters for measuring the actual number of vibrations per unit of time. Most of the apparatus fall between these two extremes.

Concrete specimens are tested for fundamental transverse, longitudinal and torsional frequencies.

As concluded by Whitehurst (34) the limitations of these techniques are:
The methods are basically applicable to specimens of a relatively small size, and because of complexity of the calculations involved in computing the constants involved, specimens must be either cylinders or prisms or uniform cross-section (square or rectangular).

2.3 Ultrasonic Pulse Velocity Method

The ultrasonic pulse velocity method is based on the transmission of an electronically generated pulse through the concrete. This method employs pulse frequencies greater than 20 kHz. The time taken for the signal to travel from the transmitting to the receiving transducer is measured electronically and displayed on a digital meter and/or a cathode-ray oscilloscope.

The relationship between acoustic parameters (pulse velocity, damping and signal shape) and the physico-mechanical characteristics of the medium, provides the means

for evaluating quality of concrete in a structure. Evaluation of concrete strength can be obtained from pulse velocity which is calculated by dividing the path length of the pulse by the travel time.

The other two characteristics, damping and signal shape, can be used for evaluation of defects such as cracks and voids in concrete. However the present study is restricted to evaluation of strength only.

Portable, high precision instruments have been developed for this test. The "V"-Meter, manufactured by James Instruments Inc., was used for this study. The equipment, shown in Fig. 2.1, consists of a C-4902 "V" meter, two C-4898 transducers, two transducer leads (3 m), and a 3-4897 reference bar.

Three alternative arrangements can be uused for placing the transducers in ultrasonic testing.

a. Direct transmission: Transducers are placed on opposite concrete surfaces.

b. Semidirect transmission: Transducers are placed on adjacent concrete surfaces which meet at an angle, usually 90 deg.

c. Indirect or surface transmission: Transducers are placed on the same surface.

Direct transmission is the most satisfactory arrangement because it gives maximum sensitivity and provides a well-defined path length. The testing points are usually established in such a way that the angle between the

Fig. 2.1 View of the V-Meter C-4902

pulse and the axis of reinforcement is not less than 30 deg. The desired temperature range during testing is from -10°C to +30°C. The path length should be measured with an accuracy of ± 0.5%. It is recommended that the path length lie within 100 to 1500 mm range.

During application of the pulse to the concrete, a tight contact between transducers and concrete is achieved by applying liquid soap, grease or Vaseline to the concrete. The type of contact material used should remain the same during testing (32).

The presence of reinforcing bars can have a major effect on pulse velocity readings. The influence is usually insignificant if the reinforcing bars run in a direction at right angles to the path and the quantity is small in relation to the path length. If reinforcing bars lie along or parallel to the pulse path, and the diameter is greater than 10 mm, measurements of pulse velocity become high and not representative of the concrete quality. Relationships are given by Chung (12) and Bungey (10) to compensate for the presence of reinforcing bars.

2.4 Rebound Method

The rebound method was applied to concrete testing in 1948 by a Swiss engineer named Ernst Schmidt. A similar method used for determining the hardness of metals had been known since 1911.

There are two types of Schmidt's hammers used in the

rebound method. Model I has external springs, and Model II has springs inside the barrel. In Model I the spring is released by a trigger. In Model II the hammer is pushed against the surface of the concrete to compress the spring by a predetermined amount. At this point the spring is automatically released. The hammer impacts against the concrete and the spring-controlled mass rebounds. The rider attached to the mass provides the reading on the guide scale, which is taken to the nearest whole number. This reading is designated as the hammer rebound number.

No theoretical relationship between rebound number and concrete strength has been established and a thorough calibration is required, as for any surface hardness tests.

Factors Influencing Results

When the rebound test is performed attention should be paid to the "fixity" of samples and flatness of the surface under impact. Poor "fixity" will result in low rebound numbers with larger effect for smaller cylinders. If the surface under testing is not flat, such as the side of a cylinder, the probability of a glancing blow increases, resulting in a false reading.

Rebound readings are affected by many factors including surface carbonation, moisture content, cement content and aggregate type. It has been proven by many investigations that there is a general correlation between compressive strength of concrete and hammer rebound number. However the

accuracy of the method is not better than ± 15 to 20 percent for laboratory conditions and a carefully calibrated hammer. In structures the scatter is expected to be greater than ± 25 percent (22).

2.5 Pull-out Tests

This test, first described by Scramtaev (27), was a simultaneous invention of two engineers: Volf and Gershberg, USSR. In this method a rod with spherically thickened end was embedded into structure. At a certain age of concrete this rod was pulled out. Owing to its shape it was pulled out toether with a cone of concrete. The concrete was simultaneously in tension and shear, with generating lines of the cone running approximately at an angle of 45 degrees.

High correlation between pulling effect and compressive strength of concrete was obtained. In 1944 Tremper (33) published his results of pull-out tests and confirmed good correlation with compressive strength. Recent results were reported by Malhotra and Garette (21); Chabowski and Cryden-Smith (11); Yener and Chen (35), with coefficient of correlation between pullout and compressive strength in the range of 0.82 and 0.91.

2.6 Drilled Cores

In order to calibrate and compare the nondestructive tests a so-called "actual strength" of concrete has to be established. For this purpose one can use either standard

150x300 mm cylinders, which have to be cast from the same batches of concrete as the structure tested, or in the case of existing structures, by means of drilled cores. Relationships between compressive test results on cylinders and cores are given by Bloem (9).

Procedures for drilling and testing are specified in ASTM Standards (5,4). The drilled core has to be at least 102 mm in diameter.

Cores are tested according to the method of test for compressive strength of molded cylinders. Compressive strength is calculated using the computed cross-sectional area based on the average diameter of the specimen. Standard L/d ratio for cores is 2. If the ratio of length to diameter is less than 2, a correction factor less than 1 must be applied to the failure load according to the ASTM Standards (5). In order to account for variation in diameters correction factors have been proposed by Kesler (18).

2.7 Correlation between Nondestructive Testing of Concrete and Compressive Strength Tests

2.7.1 Ultrasonic Pulse Velocity vs. Concrete Strength

It has been recognized that the ultrasonic pulse velocity method provides a good indication of the uniformity of concrete quality. However, a thorough calibration is required to relate pulse velocity to compressive strength.

A number of researchers have proposed expressions relating compressive strength and pulse velocity (Chung and Law, 13; Samarin and Dhir, 24; Facaoary, 15).

Chung and Law (13) reported a significant correlation between the pulse velocity in the cement paste and the compressive strength. They proposed an empirical correlation formula

$$f'_c = A\, e^{BV_p} \tag{2.1}$$

where A and B are empirical constants. V_p is the pulse velocity in the cement paste which is derived from the measured pulse velocity in concrete and assumed pulse velocities in the coarse and fine aggregate. Based on laboratory tests, values of the constants A and B were determined leading to the relationship

$$f'_c = 4.776\, e^{0.558V_p} \tag{2.2}$$

with a coefficient of correlation of 0.98. This high correlation is nevertheless offset by the fact that the method requires knowledge of the values of coarse and fine aggregate/cement ratios. For in-situ applications these ratios are usually unknown. Even when specified values can be obtained from the records, significant variations can be expected depending on quality control of batching and placement of concrete.

In order to evaluate the influence of variations in different concrete parameters on the relationship pulse velocity versus compressive strength statistical modelling can be applied as described by Gorshkov (17).

2.7.2 Rebound Number vs. Concrete Strength

Numerous investigations have been undertaken since the invention of the rebound hammer in order to calibrate rebound numbers with the concrete strength. Manufacturers of the instrument provide calibration diagrams and charts and recommend their use for estimating strength properties of the concrete. However it is generally considered necessary to develop a calibration chart for each structure tested. Calibration curves obtained by different investigators are also described by Tanigawa et al. (31). The expected accuracy of the method is described by Facaoary (15).

2.7.3 Combined Rebound and Pulse Velocity Method

As reported by Facaoary (15), Samarin and Dhir (24) and others the combined method, also known as SONREB Method, is based on combining measurements of rebound numbers and pulse velocity.

This method was introduced to avoid some of the limitations of the single methods. According to Facaoary it is actually not influenced by moisture content and maturity of concrete and less influenced by cement content and

aggregate grading, in respect to ultrasonic method, and less influenced by carbonation effects, as compared with rebound method.

In Romania, estimation of concrete strength by this method is based on a system of iso-strength curves for a reference concrete. The reference concrete is defined by the type and amount of cement and nature and grading of aggregates.

When the tested concrete is not a reference one the result obtained from iso-strength curves is multiplied by a correlation factor.

In case where the composition of the tested concrete is unknown this factor is obtained from testing of cores, and when the composition of the tested concrete is known it is calculated as a product of a series of coefficients of influences.

A similar method developed in Australia (24) requires only the knowledge pf aggregate type and approximate age of concrete. The multi-regression equation used was

$$f'_c = A_o + A_1 R + A_2 V^4$$

where f'_c = cylinder compressive strength

R = hammer rebound number

V = ultrasonic pulse velocity

A_o, A_1, A_2 = constants.

In the majority of field applications the in-laboratory

developed correlations were applied. In order to minimize the effect of moisture variation it was suggested to keep at least the surface layer of concrete being investigated saturated prior to taking nondestructive test measurements.

2.7.4 Combined Density and Pulse Velocity Method

Adil (1) has proposed to use the acoustic impedance (the product of ultrasonic pulse velocity and density) in order to achieve a better measure of concrete strength than either test alone. He also reported an excellent correlation ($r = 0.985$) of concrete density and back scattered gamma-radiation, which indicates that with a proper calibration the back-scatter counts can be used instead of direct density measurements. Along the same line Reynold et al. (23) proposed the application of gamma-ray absorption technique as a measurement of concrete density.

3. DATA ACQUISITION

3.1 Introduction

Procedures of this investigation were designed to test some practical methods of evaluations of bridge superstructures, as well as to provide data which would assist in future investigations. A similar study conducted on a reinforced concrte building is described by Gardner and Hatcher (16). Investigations on concrete bridge foundations by nondestructive methods are described by Scanlon et al. (26).

3.2 Bridge Description

The investigation was conducted on a 34-year-old two-lane highway bridge located on Highway 23 North of Lethbridge, Alberta. The bridge was designed for H-20-44 AASHO 1944 (2) truck loading on each lane and provided a passage over a Lethbridge Northern Irrigation District (LNID) canal. The view of the bridge at the time of this investigation is shown in Fig. 3.1.

The superstructure of the bridge consists of three continuous concrete spans 40 ft, 60 ft, and 40 ft (12.2 m, 18.3 m, 12.2 m) long. The spans were cast in place and made of five T-girders. The design depth of the girders varies from 4'9" (1448 mm) over the piers to 2'3" (686 mm) over the abutments and at the centre. The design depth of the deck is 7" (178 mm) with a 6" (152 mm) haunch transition to the

Fig. 3.1 View of the Tested Bridge

stem. The design thickness of the girder stem is 17" (432 mm). Eight concrete diaphragms spaced at approximately 20 ft (6.1 m) centres were placed monolithically with the deck and girder stems. Details of the bridge superstructure are shown in Fig. 3.2. The substructure of the bridge consists of two concrete spill-through abutments and two concrete piers on concrete spread footings.

Minimum 28-day compressive strength of concrete was specified as 3000 psi (20.7 MPa). Reinforcement was provided in the form of deformed and non-deformed square and round steel bars. The deck was covered with 3 1/8" (80 mm) asphalt pavement.

To identify test locations for ultrasonic and rebound measurements, and to identify core locations, a grid was marked on the girder stems. The grid divides each stem into 92 cells, each approximately 350 mm deep and 400 mm wide as shown in Fig. 3.3. Testing was limited to the middle span only.

3.3 Sampling Procedure

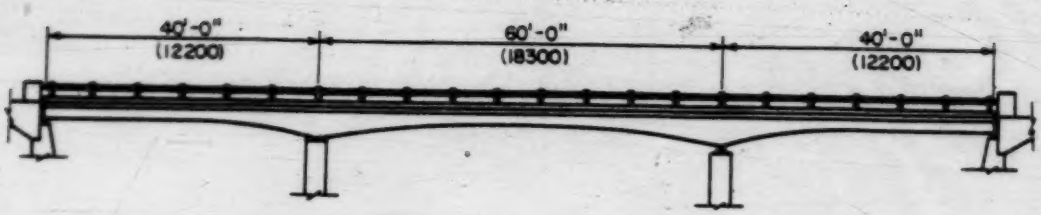
3.3.1 Grid Layout

Each cell is identified as follows,

a) Girder number A to E, ordered from west to east

b) Zone within girder: N = north zone
M = middle zone
S = south zone, and

c) Cell number within zone: 1 to 38 for zones N and S,



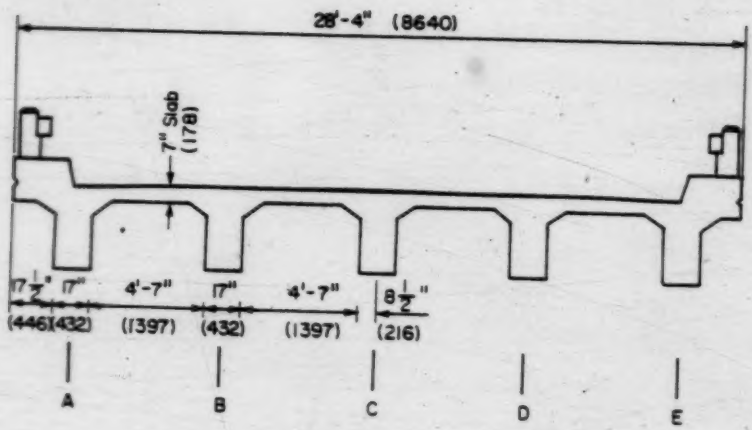


Fig. 3.2 The Elevation and a Cross-Section of the Bridge Superstructure

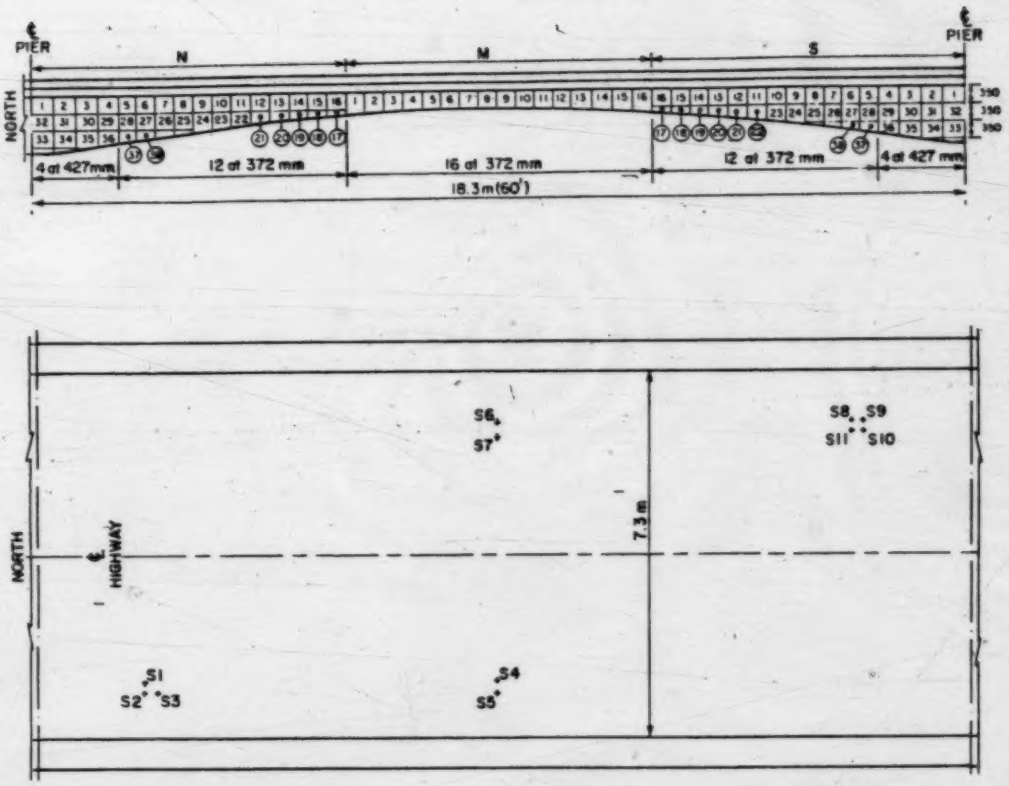


Fig. 3.3 Grid Layout on the Middle Span of the Bridge and Locations of Cores in the Bridge Deck

1 to 16 for zone M.

As an example, using this labelling scheme, the cell defined by AM12 indicates cell number 12 in the middle zone of girder A.

3.3.2 Test Locations for Ultrasonic Testing

The grid layout was marked on both vertical surfaces of each stem. For the cells of N and M zones the southern vertical border lines of the grids were selected as test locations. For the cells of S zones, the northern border lines were selected. Each point on one surface had a counterpoint on the opposite surface. Locations of the counterpoints were established through measurements along and across the grid to ensure that each pair of related points was located on a perpendicular to the vertical stem surface.

Drawings were checked to ensure that there were no reinforcing bars along the pulse path and that any transverse bars did not exceed 13 mm in diameter, which was the size of stirrups.

3.3.3 Test Locations for Rebound Testing

On each grid cell nine rebound numbers were taken in the following sequence:

9 8 7

4 5 6

3 2 1

3.3.4 Core Locations

The core locations on girder stems were identical to the locations for ultrasonic testing. Prior to coring on girder stems a magnetic inductance meter (also known as a pachometer) was used to identify the locations without reinforcement.

The core locations on the slab were designated as shown in Fig. 3.3. The locations with only one transverse reinforcing bar were established by trial and error. These locations provided at least 200 mm steel free length of core. The cores were assigned numbers S1 to S11.

3.4 Methods of Test

3.4.1. Ultrasonic Testing

Ultrasonic testing was conducted with a C-4902 "V"-meter manufactured by James Instruments Inc. The digital display showed the pulse propagation time in μsec with accuracy of 0.1 μsec. Prior to the test a thin layer of grease was applied to each testing point. A calibration rod supplied with the "V"-meter was referred to every 3-4 hours to check and adjust if necessary the zero reading of the instrument. The transducer and the receiver of the "V"-meter were applied to the correlated points on the opposite

faces and the lowest displayed time readings were recorded.

Measurements of the pulse path were taken by using a specially built rigid caliper as shown in Fig. 3.4. The caliper had a reference distance between the ends of its parallel and equal branches. This distance was checked every 20 minutes with a steel tape to the nearest 0.2 mm and adjusted to remain constant within each zone of the girder.

The end of one branch was always placed tightly against the test point. Verticality of the branches and horizontality of the base were controlled with levels. The measurements of distance d as shown in Fig. 3.4 were taken with a sliding caliper to the nearest 0.1 mm. The desired path lengths were obtained by subtracting measured distances from the reference distance of the rigid caliper.

3.4.2 Rebound Testing

Rebound testing was conducted with an H-Meter Model C-7311 manufactured by James Instrument Inc. in the sequence shown previously and in accordance with ASTM Standards (7). During the tests the hammer was held perpendicular to the tested concrete surface. The spring-loaded mechanism was released automatically and the rebound number was recorded from the scale provided on the side of the H-meter.

3.4.3 Dimensions

Measurements were taken for dimensions of the slab and stems of the superstructure. The slab dimensions were

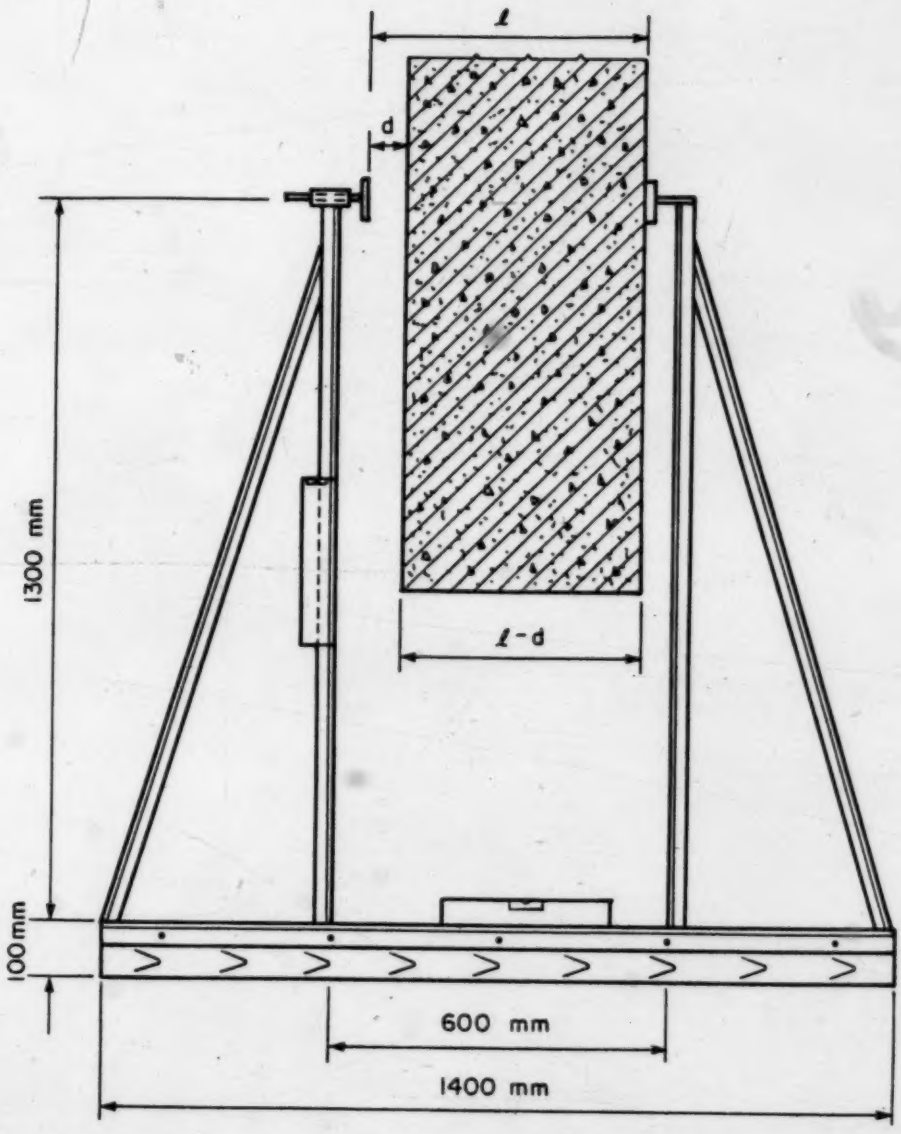


Fig. 3.4 Rigid Caliper for Girder Stem Thickness Measurements

obtained by coring through the slab at seven locations. The vertical stem dimensions (including the haunch below slab) were obtained by using a device consisting of a steel square edge, clamps, levels and a rigid scale as shown in Figs. 3.5 and 3.6. Stem thickness measurements are described in 3.4.1. Length of each beam of the middle span was measured with a steel tape to the nearest mm.

3.4.4 Coring

Cores were drilled with a 4 in. (102 mm) diameter diamond drill. The stem thickness was approximately 430 mm. Therefore the first core had to be broken off at an approximate length of 200 mm and removed. Then the second core was drilled. When drilling through the slab attempts were made to avoid presence of two cross-bars in the core. This was achieved by locating the top cross-bar with the initial core and shifting the drill away from the top bar for the next core. To check the accuracy of stem thicknesses obtained with the caliper the corresponding half of the cores from girder stems were put back together and secured with a clamp. Then the length of the whole core was measured with a sliding caliper to the nearest 0.1 mm and compared with the data obtained by the rigid caliper at the same location.

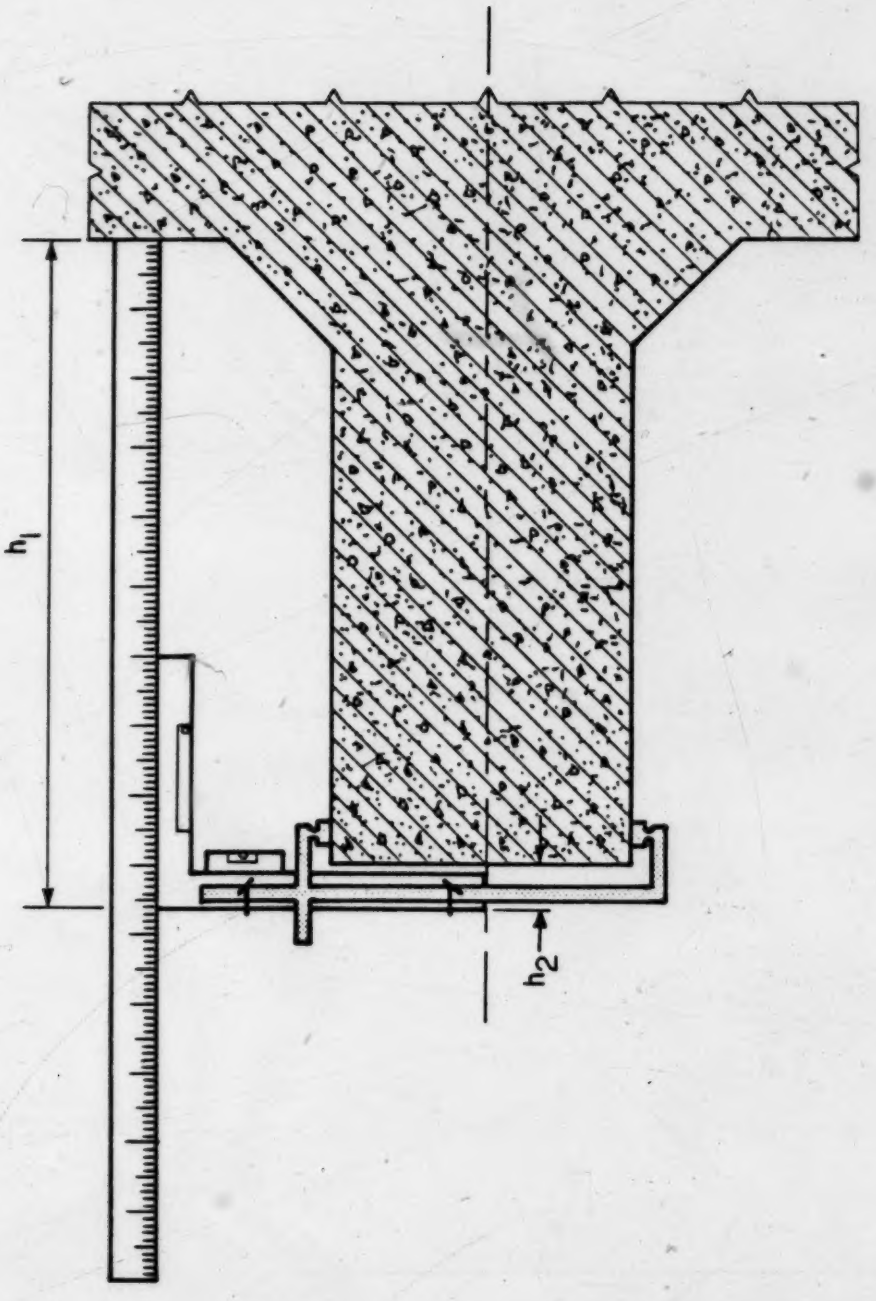


Fig. 3.5 Measurement of Girder Stem Height

Fig. 3.6 View of the Stem Height Measuring Device

4. PRESENTATION OF DATA

4.1 Introduction

In this chapter the data obtained using the methods described in Chapter 3 are presented. The data consist of pulse velocity measurements, rebound measurements, dimension measurements, compressive strengths of cores, and density measurements.

4.2 Pulse Velocities

In-situ pulse velocities were obtained for the five girder stems in the middle span only. Continuous traffic on the bridge and the need to remove the asphalt pavement from the deck prior to application of the V-meter excluded the possibility of performing similar tests on the deck.

Test locations were established using grids shown in Fig. 3.2. Readings were taken at a total of 454 locations on the five girders. Six locations, AS35 to AS38, BS37, and BS38 were excluded as having rough surfaces, preventing proper contact between transducers and concrete surfaces.

The data required for calculating pulse velocities are the time taken for the pulse to travel between the transducers, and the path length of the pulse. The first was obtained using the V-meter and the second using the rigid caliper as described in Section 3.4.1. Data consisting of the pulse travel time, path length, and corresponding pulse velocity are presented in Appendix A

Tables A1 to A15 for all test locations. An example of the data thus obtainied is shown in Table 4.1 for Zone AM.

For each test point the V-meter provided time readings t in μsec and the measurements with the rigid caliper gave distances d in mm as shown in Fig. 3.5. The time readings were then reduced by 2.4 μsec to account for the loss of pulse velocity due to surface roughness. Adjusted time readings were entered into the tables as τ (μsec). The value of 2.4 μsec is based on laboratory tests on cores, conducted as part of this investigation and described in Section 3.2.1. Table B1 in Appendix B shows the calculation of the value of 2.4 μsec.

To calculate the path length, the distance d (mm) was subtracted from the caliper reference distance and results were presented in the tables as the value ℓ (mm). The pulse velocity V at each test location was calculated as $V = \ell/\tau$ (mm/μsec).

The effect of reinforcement on pulse velocity was ignored at all locations except three: ES15, ES16 and ES17. At these locations the time readings were much lower than in the rest of the girder. Pachometer readings at these points confirmed the presence of a significant amount of steel. Therefore the values of pulse velocities at these three locations were excluded from further statistical analysis. The pachometer was applied at about 80 other locations to confirm that reinforcement in other test locations was minimal as implied by the design drawings.

Table 4.1 Pulse Velocity Data for Zone AM

Point Number	Time Reading, t (μsec)	d (mm)	Path Length ℓ = 529-d (mm)	Adjusted Time τ = t-2.4 (μsec)	Pulse Velocity, V $(\frac{mm}{\mu sec})$
1	2	3	4	5	6
1	117.6	85.1	443.9	115.2	3.853
2	115.8	83.4	445.6	113.4	3.929
3	112.7	90.5	438.5	110.3	3.976
4	112.2	93.5	435.5	109.8	3.966
5	113.7	94.5	434.5	111.3	3.961
6	113.3	94.0	435.0	110.9	3.922
7	106.3	97.4	431.6	103.9	4.154
8	114.6	96.0	433.0	112.2	3.859
9	115.0	96.5	432.5	112.6	3.841
10	111.2	97.5	431.5	108.8	3.966
11	114.2	95.5	433.5	111.8	3.877
12	109.7	96.3	432.7	107.3	4.033
13	112.3	94.5	434.5	109.9	3.954
14	106.4	96.0	433.0	104.0	4.163
15	111.0	97.0	432.0	108.6	3.978
16	109.7	101.5	429.5	107.3	4.003

Pulse velocities for all test locations are summarized in the histogram shown in Fig. 4.1. The mean pulse velocity is 3.971 mm/μsec with a standard deviation of 0.161 mm/μsec and coefficient of variation equal 4.05 percent. Additional histograms are plotted in Appendix A Figures A21 to A35 to show the variation of pulse velocity within each of the 15 girder zones (3 zones in each of 5 girders).

4.3 Rebound Readings

In-situ rebound readings were taken on girder stems only as described in Section 3.3.3. Nine readings were taken within each cell of the grid shown in Fig. 3.2, except for 3 cells: AS36, AS37, AS38 due to their roughness. Readings were taken on a total of 457 cells. An example of the data is shown in Table 4.2 for zone BM. The data for all test locations are presented in Appendix A Tables A16 to A30.

Rebound readings were also taken around the locations of 32 cores drilled from girder stems. At each location 8 readings were obtained at the points equally spaced on a 150 mm circle concentric with a 102 mm core hole. The data of the rebound number around each core hole, as well as the mean, minimum and maximum rebound numbers are shown in Table 4.3.

4.4 Dimensions

To evaluate the dimensional properties of the bridge,

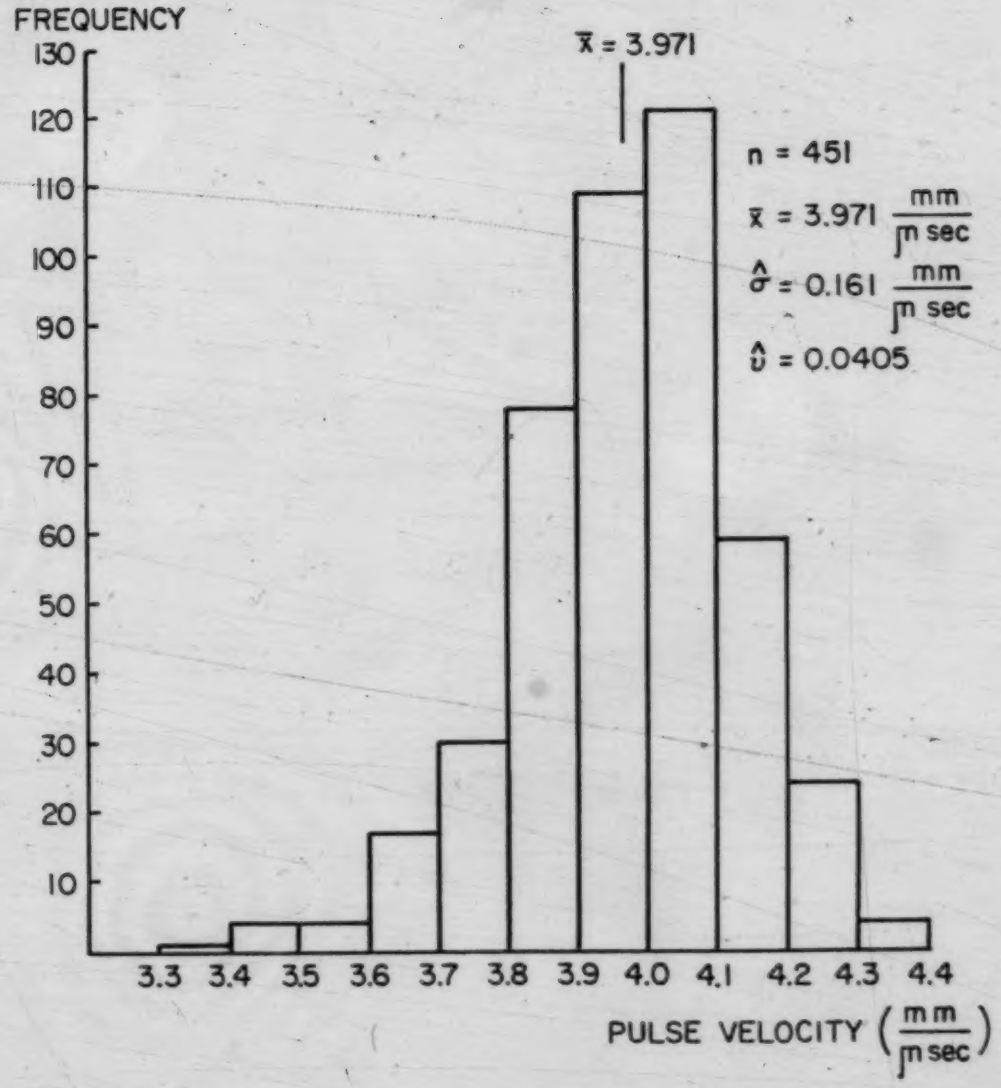


Fig. 4.1 Histogram of Pulse Velocities in Girder Stems

Table 4.2 Rebound Numbers in Cells of Zone BM

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	45	55	51	54	56	57	53	48	54	42.6	45
2	50	52	49	54	54	58	46	40	50	50.3	40
3	56	46	50	55	54	55	44	50	45	50.6	44
4	49	42	49	52	53	52	42	45	40	47.1	40
5	52	50	53	51	50	48	40	46	45	48.3	40
6	51	51	49	45	53	51	41	48	48	48.6	41
7	53	46	44	47	43	53	45	46	51	47.6	43
8	48	52	42	55	51	52	49	46	48	49.2	42
9	54	54	44	51	55	48	46	54	53	51.0	44
10	52	45	44	52	52	54	49	57	53	50.9	44
11	51	43	47	41	54	41	57	48	47	47.7	41
12	51	53	45	49	53	45	44	51	51	49.1	44
13	52	47	51	52	50	48	53	54	50	50.8	47
14	50	46	52	48	50	51	55	50	47	49.9	46
15	50	50	54	51	48	55	50	49	55	51.3	48
16	47	52	48	43	45	51	52	48	48	42.9	43

Table 4.3 Rebound Numbers Around Core Holes In-Situ

No.	Point Number	Rebound Number								Mean	Min	Max
		1	2	3	4	5	6	7	8			
1	2	3	4	5	6	7	8	9	10	11	12	13
1	AN#32E	49	45	46	50	42	44	32	51	44.9	32	51
2	AN#32W	44	40	39	44	43	35	52	44	42.6	35	52
3	AN#29E	46	49	38	51	44	51	48	50	47.1	38	51
4	AN#29W	49	49	42	49	46	39	42	51	45.9	39	51
5	AN#23E	35	38	40	35	37	39	38	43	38.1	35	43
6	AN#23W	36	44	36	28	31	47	37	38	37.1	28	47
7	BN#31W	47	43	47	41	36	40	50	34	42.2	34	50
8	BN#31E	49	54	46	52	52	51	52	43	49.9	43	54
9	BN#8W	46	48	49	43	46	37	42	37	43.5	37	49
10	BN#8E	43	50	51	45	49	46	43	48	46.9	43	51
11	BN#4W	39	45	36	42	41	47	36	45	41.4	36	47
12	BN#4E	35	44	41	37	44	45	33	40	39.9	33	45
13	CN#5W	52	46	31	40	47	44	42	49	43.9	31	49
14	CN#5E	47	42	45	33	38	47	44	38	41.8	33	47
15	CN#1W	31	49	42	48	46	44	40	35	41.9	31	48
16	CN#1E	50	44	43	40	45	41	48	41	44.0	40	50
17	DN#3W	39	48	38	41	38	37	38	48	40.9	38	48
18	CN#3E	34	50	44	32	38	47	33	40	39.8	32	47
19	EN#8W	35	41	44	45	44	30	39	43	40.1	30	45
20	EN#8E	44	41	42	39	39	41	36	43	40.6	36	44
21	AM#9E	48	48	43	50	39	43	38	48	44.6	39	48
22	AM#9W	37	43	50	33	38	48	40	33	40.2	33	50
23	AS#5E	51	43	43	44	45	44	43	45	44.8	43	51
24	AS#8E	37	47	46	43	41	39	41	49	42.9	37	49
25	BS#3E	34	33	42	41	45	42	38	35	38.9	33	45
26	BS#7E	37	40	43	34	40	39	40	41	39.2	34	43
27	CS#1E	42	46	50	50	47	47	46	48	47.0	42	50
28	CS#5E	44	48	36	37	39	33	39	41	39.6	33	48
29	DS#31E	46	49	54	51	45	42	32	42	45.1	32	54
30	DS#4E	50	36	52	45	45	42	43	44	44.6	36	52
31	ES#29W	39	53	31	39	34	41	46	44	40.9	31	53
32	ES#23W	47	48	40	40	35	52	40	46	43.2	35	52

measurements were taken of deck thickness, stem thickness, stem height, and span length. The deck thicknesses were obtained from 7 cores drilled through the deck at random locations. The data are presented in Table 4.4 as L_H (mm). Stem thicknesses were measured using the rigid caliper as described in Section 3.4.1. The data are presented in Tables A1 to A15 of Appendix A. Histograms are also plotted in Appendix A Figures A5 to A19 to show the variation of stem thicknesses within each of 15 zones. In order to evaluate the accuracy of the rigid caliper, the lengths of 11 cores were measured after removal from the stems. The results shown in Table 4.5 indicate that the measurements by caliper agree very well with the direct measurements of the core lengths.

The heights of girder stems were obtained at 65 locations, i.e. 13 locations on each girder. Due to the symmetry of the specified girder profile, 13 locations of measurements corresponded to 7 specified values of girder heights. The data are presented in Tables 4.6 and 4.7.

The length of each of 5 girders of the middle span was measured with a steel tape to the nearest 5 mm. The measurements were taken from bearing centre to bearing centre. The data are shown in Table 4.8.

4.5 Core Test Results

4.5.1. Pulse Velocity

Four groups of cores were obtained from the middle span

Table 4.4 Length of Cores Drilled Through the Deck

No.	Core Number	Length L_H mm
1	S1	246.6
2	S3	245.1
3	S4	266.1
4	S5	268.0
5	S6	260.6
6	S7	259.6
7	S11	268.0

Table 4.5 Evaluation of the Accuracy of the Rigid Caliper

No.	Core Number	Stem Thickness by Caliper ℓ_1 (mm)	Stem Thickness from Cores ℓ_2 (mm)	Percent Difference $(\frac{\ell_1-\ell_2}{\ell_1}) \times 100$ (%)
1	AN#23	440.5	440.6	-0.02
2	AN#29	431.4	432.8	-0.32
3	AN#32	426.4	424.9	0.35
4	AM#9	432.5	434.1	-0.37
5	BN#4	440.8	440.2	0.14
6	BN#8	434.3	434.7	-0.09
7	BN#31	441.7	440.7	0.23
8	CN#1	434.0	434.2	-0.05
9	CN#5	424.3	425.7	0.33
10	DN#3	456.5	457.9	-0.30
11	EN#8	445.0	446.3	0.29
	Mean	437.04	437.46	0.017

Table 4.6 Measurements of Girder Heights

No.	Distance from Previous Point, mm	Specified Dimension	Measured Dimensions, mm		
			From Level to Bottom of Deck	From Level to Bottom of Stem	Net Dimension (4)-(5)
1	2	3	4	5	6
			AN, AM, AS		
1	228.6	1270.0	1333	50	1283
2	1485.9	1036.6	1072	50	1022
3	1485.9	847.7	881	51	830
4	1485.9	698.5	757	50	707
5	1485.9	592.1	669	64	605
6	1485.9	528.6	580	51	529
7	1485.9	508.0	566	52	514
8	1485.9	528.6	586	51	535
9	1485.9	592.1	631	29	602
10	1485.9	698.5	756	54	702
11	1485.9	847.7	900	53	847
12	1485.9	1036.6	1094	51	1043
13	228.6	1270.0	1287	25	1262
			BN, BM, BS		
1	228.6	1270.0	1326	52	1274
2	1485.9	1036.6	1066	50	1016
3	1485.9	847.7	873	52	821
4	1485.9	698.5	717	52	665
5	1485.9	592.1	620	51	569
6	1485.9	528.6	569	50	519
7	1485.9	508.0	566	52	514
8	1485.9	528.6	582	50	532
9	1485.9	592.1	603	38	565
10	1485.9	698.5	714	52	662
11	1485.9	847.7	866	56	810
12	1485.9	1036.6	1072	56	1016
13	228.6	1270.0	1285	19	1266
			CN, CM, CS		
1	228.6	1270.0	1330	53	1277
2	1485.9	1036.6	1128	51	1077
3	1485.9	847.7	915	50	865
4	1485.9	698.5	749	55	694
5	1485.9	592.1	647	51	596
6	1485.9	528.6	574	51	523
7	1485.9	508.0	559	50	509

Table 4.6 Continued

No.	Distance from Previous Point, mm	Specified Dimension	Measured Dimensions, mm		
			From Level to Bottom of Deck	From Level to Bottom of Stem	(4)-(5)
1	2	3	4	5	6
		CN, CM, CS (continued)			
8	1485.9	528.6	576	50	526
9	1485.9	592.1	614	34	580
10	1485.9	698.5	712	52	660
11	1485.9	847.7	873	50	823
12	1485.9	1036.6	1060	50	1010
13	228.6	1270.0	1276	18	1258
		DN, DM, DS			
1	228.6	1270.0	1324	54	1270
2	1485.9	1036.6	1100	50	1050
3	1485.9	847.7	897	50	847
4	1485.9	698.5	761	60	701
5	1485.9	592.1	674	71	603
6	1485.9	528.6	562	51	511
7	1485.9	508.0	567	60	507
8	1485.9	528.6	556	59	497
9	1485.9	592.1	593	30	563
10	1485.9	698.5	726	52	674
11	1485.9	847.7	877	50	827
12	1485.9	1036.6	1068	54	1034
13	228.6	1270.0	1294	19	1275
		EN, EM, ES			
1	228.6	1270.0	1311	50	1261
2	1485.9	1036.6	1093	50	1043
3	1485.9	847.7	901	50	851
4	1485.9	698.5	756	50	706
5	1485.9	592.1	674	69	605
6	1485.9	528.6	581	50	531
7	1485.9	508.0	535	54	479
8	1485.9	528.6	576	53	523
9	1485.9	592.1	616	26	590
10	1485.9	698.5	747	50	697
11	1485.9	847.7	890	51	839
12	1485.9	1036.6	1097	56	1043
13	228.6	1270.0	1291	20	1271

Table 4.7 Means of Measured Dimensions vs. Specified Dimensions of Girder Stem Heights

Section No.	Specified Dimension h_s (mm)	Mean of Measured Dimensions h_m (mm)
1	1270.0	1269.7
2	1036.6	1035.4
3	847.7	836.0
4	698.5	686.8
5	592.1	587.8
6	528.6	522.6
7	508.0	504.6

Table 4.8 Girder Lengths of the Middle Span

No.	Girder Number	Specified Span L_S mm	Measured Span L_m mm	$L_m - L_s$ mm	L_m / L_s
1	2	3	4	5	6
1	A	18288	18261	-27	0.998
2	B	18288	18234	-54	0.997
3	C	18288	18252	-36	0.998
4	D	18288	18310	+22	1.001
5	E	18288	18333	+45	1.002
				Mean	0.999

of the bridge. The first group consists of 11 pairs of cores, each pair drilled from the same location in a girder stem. When put together before any cutting, each pair provided the full width of the stem at the respective location.

The second group consists of 10 single cores from girder stems. Each core length was about one-half of the stem thickness.

The third group consists of 7 cores drilled through the full depth of the deck. These cores had 1 or 2 inclusions of transverse bars, 13 mm in diameter.

The fourth group consists of 4 cores with lengths about one half the depth of the deck.

Prior to compressive strength testing, each core was subjected to the pulse velocity test with the V-meter. Prior to V-meter testing the broken end of each core of the groups 1, 2 and 4 was cut with a diamond blade to provide a smooth end surface. The other end retained its natural roughness. The cores of Group 3 were tested initially with both natural ends. The V-meter was applied and time readings and lengths of cores were recorded as shown in Tables 4.9, 4.10, 4.11, 4.12 and 4.13.

The cores of all 4 groups were tested with and without natural rough ends. The cores of the third group were also tested before and after elimination of steel bar inclusions as shown in Table 4.14.

Table 4.9 Data on Pulse Velocity Tests on Cores of the Group #1

No.	Core Number	Ends Rough and Smooth: Length L_i mm	Ends Rough and Smooth: Time Reading t_i μsec	Ends Rough and Smooth: V_i mm/μsec	Both Ends Smooth: Length L_j mm	Both Ends Smooth: Time Reading t_j μsec	Both Ends Smooth: V_j mm/μsec	L_i/V_j μsec
1	2	3	4	5	6	7	8	9
1	AN#23W	228.0	55.1	4.138	202.6	47.4	4.274	53.3
2	AN#23E	185.2	47.5	3.899	180.5	45.2	3.993	46.4
3	AN#29W	215.2	49.3	4.365	203.6	47.5	4.286	50.2
4	AN#29E	191.3	45.3	4.223	181.3	41.8	4.337	44.1
5	AN#32W	214.6	51.3	4.183	202.6	47.6	4.256	50.4
6	AN#32E	178.5	44.4	4.020	174.3	40.6	4.293	41.6
7	AM#9W	218.4	53.8	4.059	203.3	47.0	4.326	50.5
8	AM#9E	188.5	49.4	3.816	184.6	44.8	4.120	45.8
9	BN#4W	221.6	54.3	4.081	173.1	40.8	4.242	52.2
10	BN#4E	191.0	48.1	3.971	143.6	35.6	4.034	47.3
11	BN#8W	224.0	55.4	4.043	191.9	46.4	4.136	54.2
12	BN#8E	185.8	47.0	3.953	180.5	44.2	4.084	45.5
13	BN#31W	231.4	56.7	4.081	203.9	48.6	4.195	55.2
14	BN#31E	193.5	45.1	4.290	188.2	43.5	4.326	44.7
15	CN#1W	215.0	55.2	3.895	204.1	52.1	3.917	54.9
16	CN#1E	181.8	48.2	3.772	176.8	45.1	3.920	46.4
17	CN#5W	212.2	52.0	4.081	203.0	47.7	4.256	49.9
18	CN#5E	185.0	44.2	4.186	181.2	42.5	4.263	43.4
19	DN#3E	244.3	58.7	4.162	203.6	47.7	4.268	57.2
20	DN#3W	190.6	47.0	4.055	186.6	45.0	4.147	46.0
21	EN#8E	223.6	54.8	4.080	203.2	48.8	4.164	53.7
22	EN#8W	201.0	48.4	4.153	199.3	46.3	4.304	46.7
				Σ1111.2				Σ1079.6

Table 4.10 Data on Pulse Velocity Tests on Cores of the Group #2

No.	Core Number	Ends Rough and Smooth: Length L_i mm	Time Reading t_i μsec	V_i mm/μsec	Both Ends Smooth: Length L_j mm	Time Reading t_j μsec	V_j mm/μsec	$\frac{V_i}{V_j}$ μsec
1	2	3	4	5	6	7	8	9
1	AS#5E	232.2	57.5	4.038	204.4	49.5	4.129	56.2
2	AS#8E	244.3	60.4	4.035	202.0	47.0	4.299	56.8
3	BS#3E	223.0	56.9	3.919	203.0	51.1	3.972	56.1
4	BS#7E	286.2	72.4	3.953	204.1	49.2	4.148	69.0
5	CS#1E	262.4	60.4	4.344	203.3	46.4	4.381	59.9
6	CS#5E	271.3	66.7	4.067	203.5	48.4	4.204	64.5
7	DS#4E	254.1	58.4	4.351	203.6	46.4	4.388	57.9
8	ES#31E	274.7	66.8	4.112	203.0	49.1	4.134	66.4
9	ES#29W	246.7	62.5	3.947	194.5	48.1	4.035	61.1
10	ES#23W	230.6	57.2	4.031	203.0	50.2	4.044	57.0
			Σ 619.20					Σ 604.90

L_i = length of core with one natural and the other smooth cut end

t_i = time reading in the core with one natural and the other smooth cut end

V_i = pulse velocity in the core with one natural and the other smooth cut end

L_j = length of the core with two smooth cut ends

t_j = time reading in the core with two smooth cut ends

V_j = pulse velocity in the core with two smooth cut ends

Table 4.11 Data on Pulse Velocity Tests on Cores of the Group #3

No.	Core Number	Both Ends Rough			Both Ends Smooth			Number of Transverse Bars
		Length L_H mm	Time Reading t_H μsec	V_H $\frac{mm}{\mu sec}$	Length L_j mm	Time Reading t_j μsec	V_j $\frac{mm}{\mu sec}$	
1	2	3	4	5	6	7	8	9
1	S1	246.6	59.3	4.158	225.6	51.0	4.423	2
2	S3	245.1	56.3	4.353	232.2	50.9	4.562	1
3	S4	266.1	63.7	4.177	256.7	57.7	4.438	1
4	S5	268.0	66.8	4.012	257.7	62.2	4.143	2
5	S6	260.6	62.1	4.196	244.4	56.3	4.341	1
6	S7	259.6	60.0	4.327	246.0	54.2	4.539	1
7	S11	268.0	63.7	4.207	261.3	59.3	4.406	1

L_H = length of core with two natural ends

t_H = time reading in the core with two natural ends

V_H = pulse velocity in the core with two natural ends

L_j = length of the core with two smooth cut ends

t_j = time reading in the core with two smooth cut ends

V_j = pulse velocity in the core with two smooth cut ends

Table 4.12 Data on Pulse Velocity Tests on Cores of the Group #3

No.	Core Number	Ends Rough and Smooth: Length L_i mm	Time Reading t_i μsec	V_i mm/μsec	Both Ends Smooth: Length L_j mm	Time Reading t_j μsec	V_j mm/μsec	$\frac{L_i}{V_j}$ μsec
1	2	3	4	5	6	7	8	9
1	S1	241.4	56.3	4.288	225.6	51.0	4.423	54.6
2	S3	238.8	52.9	4.514	232.2	50.9	4.562	52.3
3	S4	264.0	59.9	4.407	256.7	57.7	4.438	59.5
4	S5	265.8	64.2	4.140	257.7	62.2	4.143	64.2
5	S6	252.3	58.2	4.335	244.4	56.3	4.341	58.1
6	S7	253.8	56.5	4.492	246.0	54.2	4.539	55.9
7	S11	266.2	61.7	4.314	261.3	59.3	4.406	60.4
			Σ 409.7					Σ 405.0

L_i = length of core with one natural and the other smooth cut end

t_i = time reading in the core with one natural and the other smooth cut end

V_i = pulse velocity in the core with one natural and the other smooth cut end

L_j = length of the core with two smooth cut ends

t_j = time reading in the core with two smooth cut ends

V_j = pulse velocity in the core with two smooth cut ends

Table 4.13 Data on Pulse Velocity Tests of Cores of the Group #4

No.	Core Number	Ends Rough and Smooth			Both Ends Smooth		
		Length L_i mm	Time Reading t_i μsec	V_i $\frac{mm}{\mu sec}$	Length L_j mm	Time Reading t_j μsec	V_j $\frac{mm}{\mu sec}$
1	2	3	4	5	6	7	8
1	S8	119.6	28.2	4.241	107.3	22.9	4.686
2	S9	150.0	35.0	4.286	143.7	31.2	4.605
3	S10	134.0	30.9	4.336	131.4	28.0	4.693
4	S2	-	-	-	126.2	25.5	4.949

L_i = length of core with one natural and the other smooth cut end

t_i = time reading in the core with one natural and the other smooth cut end

V_i = pulse velocity in the core with one natural and the other smooth cut end

L_j = length of the core with two smooth cut ends

t_j = time reading in the core with two smooth cut ends

V_j = pulse velocity in the core with two smooth cut ends

Table 4.14 Influence of Transverse Bars (13 mm ϕ) on the Pulse Velocity in the Core

No.	Core Number	Length L_j mm	Time t_j μsec	V_j mm/μsec			Number of Transverse Bars	Increase in Velocity Δ_v %
1	2	3	4		5		6	7
		225.6	51.0	4.423	-	-	2	2.60
1	S1	173.8	38.3	-	4.538	-	1	2.27
		134.6	29.0	-	-	4.641	0	-
		-	-	-	-	-	-	-
2	S3	232.2	50.9	-	4.562	-	1	1.27
		201.9	43.7	-	-	4.620	0	-
		-	-	-	-	-	-	-
3	S4	256.7	57.7	-	4.438	-	1	1.22
		203.5	45.3	-	-	4.492	0	-
		257.7	62.2	4.143	-	-	2	0.22
4	S5	199.7	48.1	-	4.152	-	1	0.72
		168.1	40.2	-	-	4.182	0	-
		-	-	-	-	-	-	-
5	S6	244.4	56.3	-	4.341	-	1	2.75
		203.8	45.3	-	-	4.499	0	-
		-	-	-	-	-	-	-
6	S7	246.0	54.2	-	4.539	-	1	1.27
		203.9	43.7	-	-	4.664	0	-
		-	-	-	-	-	-	-
7	S11	261.3	59.3	-	4.406	-	1	1.27
		203.9	45.7	-	-	4.462	0	-

$\bar{x}$ = 1.773%
$\hat{\sigma}$ = 1.101%
$\hat{v}$ = 62.1%

4.5.2 Dimensions

Measurements of core dimensions were required for pulse velocity and compressive strength tests. Prior to each pulse velocity test the length of each core was measured with a sliding caliper to the nearest 0.1 μm.

Prior to compressive strength test the length of each capped core and its diameter were measured with the sliding caliper according to ASTM (5).

4.5.3 Compressive Strength

Compressive strength of cores was obtained as described in Section 2.4. Cores were tested air dry. Prior to testing, density measurements were made on 25 cores using the abbreviated method of measuring weight in water and in the air. Cores #1 to 20 and #33 to 37 were tested at a rate of loading of 15 kN in 10 sec. These cores had standard (2:1) length to diameter (L/D) ratio. The other cores were tested with a rate of loading of 15 kN in 6 sec. These cores included both 2:1 and smaller L/D ratios. Compressive strength results summarized in Table 4.15 show the corrected strength for L/D ratios less than 2.0. These data are presented with corresponding pulse velocities V in mm/μsec and concrete densities ρ in Tonnes/m^3.

Table 4.15 Data on 43 Cores

No.	Core Number	$\frac{V}{\frac{mm}{\mu sec}}$ on Cores	Core Strength MPa	ρ $\frac{T}{m^3}$
1	AN#32W	4.256	43.43	2.320
2	CN#5W	4.256	32.56	2.376
3	CS#5E	4.204	38.93	2.351
4	BS#3E	3.972	29.42	2.306
5	CS#1E	4.381	45.76	2.386
6	AM#9W	4.326	43.33	2.305
7	AS#5E	4.129	41.82	2.345
8	AS#8E	4.299	37.34	2.333
9	AN#23W	4.274	38.04	2.354
10	BN#31W	4.195	33.49	2.378
11	DN#3E	4.268	35.28	2.359
12	ES#29W	4.035	27.51	2.269
13	EN#8W	4.304	38.44	2.338
14	DS#4E	4.388	44.74	2.386
15	AN#29W	4.286	44.74	2.340
16	CN#1W	3.917	21.07	2.313
17	EN#8E	4.164	41.65	2.342
18	BS#7E	4.148	32.56	2.324
19	DS#31E	4.134	35.16	2.358
20	ES#23W	4.044	29.79	2.362
21	AN#32E	4.293	36.77	-
22	CN#5E	4.263	34.34	-
23	AM#9E	4.120	36.07	-
24	AN#23E	3.993	33.73	-
25	BN#31E	4.326	47.95	-
26	DN#3W	4.147	37.31	-
27	AN#29E	4.337	44.09	-
28	CN#1E	3.920	20.33	-
29	BN#8W	4.136	35.62	-
30	BN#8E	4.084	37.28	-
31	BN#4W	4.242	37.25	-
32	BN#4E	4.034	42.85	-
33	S3	4.620	51.27	2.336
34	S7	4.664	47.46	2.348
35	S11	4.462	43.63	2.320
36	S6	4.499	49.93	2.360
37	S4	4.492	40.04	2.326
38	S2	4.949	59.95	-
39	S10	4.693	48.70	-
40	S5	4.182	38.17	-
41	S1	4.641	59.27	-
42	S8	4.686	46.10	-
43	S9	4.605	44.68	-

5. CORRELATION OF PULSE VELOCITIES, REBOUND NUMBERS AND CONCRETE DENSITIES WITH THE COMPRESSIVE STRENGTH OF CORES

5.1 Introduction

The nondestructive testing, core testing, and dimension survey performed on the bridge produced a large amount of data related either to dimensional or material properties. A limited statistical evaluation was performed on the data on dimensional properties and as presented in Chapter 4.

This chapter deals with the establishment of relationships between compressive strength, pulse velocity, rebound number, and density, based on regression analysis.

5.2 Correlation Between Pulse Velocity and Compressive Strength

A regression analysis for pulse velocities vs compressive strength was performed on data of 20 cores randomly selected from a total of 32 cores obtained from the girder stems. Prior to selection each core was assigned a number from 1 to 32. Then a random number generator program was applied. The data used are given in Table 5.1 as "random variables" and plotted as a scatter diagram in Fig. 5.1.

The correlation was established using two regression equations, one represented by the power curve, $Y = bX^a$, and the other by the exponential curve, $Y = be^{aX}$, where X = pulse velocity in mm/μsec is the independent variable, and

Table 5.1 Regression Analysis for Compressive Strength Versus Pulse Velocity Using Power Curve and Exponential Curve

No.	Core Number	Random Variables		Results of Regression Analysis	
		$X = V$ $\frac{mm}{\mu sec}$	$Y = f'_c$ (MPa)	Power Curve(1) f'_e (MPa)	Exponential Curve(2) f''_e (MPa)
1	2	3	4	5	6
1	AN#32W	4.256	43.42	38.80	38.79
2	CN#5W	4.256	32.56	38.80	38.79
3	CS#5E	4.204	38.93	36.39	36.34
4	BS#3E	3.972	29.42	27.04	27.18
5	CS#1E	4.381	45.76	45.14	45.36
6	AM#9W	4.326	43.33	42.25	42.34
7	AS#5E	4.129	41.82	33.12	33.08
8	AS#8E	4.299	37.34	40.89	40.93
9	AN#23W	4.274	38.04	39.66	39.67
10	BN#31W	4.195	33.49	35.98	35.94
11	DN#3E	4.268	35.28	39.37	39.38
12	ES#29W	4.035	27.51	29.36	29.41
13	EN#8W	4.304	38.44	41.14	41.19
14	DS#4E	4.388	44.74	45.52	45.76
15	AN#29W	4.286	44.74	40.25	40.28
16	CN#1W	3.917	21.07	25.14	25.37
17	EN#8E	4.164	41.65	34.61	34.57
18	BS#7E	4.148	32.56	33.92	33.88
19	DS#31E	4.134	35.16	33.33	33.29
20	ES#23W	4.044	29.79	23.80	29.75
Mean		$\bar{x}=4.199$	$\bar{f}'_c=36.75$	$\bar{f}'_e=36.23$	$\bar{f}''_e=36.56$
Standard Deviation		$\hat{\sigma}_x=0.131$	$\hat{\sigma}=6.648$	$\hat{\sigma}_1=6.216$	$\hat{\sigma}_2=5.724$
Correlation Coefficient				$r_1 = 0.832$	$r_2 = 0.829$

Notes: (1) Power Curve: $f'_e = bV^a = 0.020V^{5.227}$

(2) Exponential Curve: $f''_e = be^{aV} = 0.188e^{1.252V}$

Y = compressive strength of concrete in MPa is the dependent variable. The best fit curves thus obtained are: The power curve $y = 0.020X^{5.227}$ or $f'_e = 0.020V^{5.227}$ and the exponential curve $y = 0.188e^{1.252V}$ or $f''_e = 0.188e^{1.252V}$, where f'_e and f''_e are the estimated values of concrete strength in MPa and V is the pulse velocity in mm/μsec.

The coefficient of correlation for the power curve is r = 0.832, which is slightly higher than r = 0.829 for the exponential curve.

The values of the estimated concrete strength for each model are shown in Table 5.1 as the "results of regression analysis". The mean values of the estimated concrete strength from the power curve was $\bar{f}'_e$ = 36.23 MPa and from the exponential curve was $\bar{f}''_e$ = 36.56 MPa less by 1.4% and 0.5% respectively than the actual mean value of 36.75 MPa of the compressive strength of cores.

The standard deviations of the estimated concrete strength were 6.216 MPa for the power curve and 5.724 MPa for the exponential curve. Thus the standard deviation for the power curve was 6.5% smaller and for the exponential curve 13.9% smaller than the actual standard deviation of 6.648 MPa of the compressive strength of cores. This indicates that the variability of actual concrete strength is greater than the variability of the estimated concrete strength based on pulse velocity alone.

In further analysis preference was given to the power curve model. Fig. 5.1 shows the established relationship f'_e

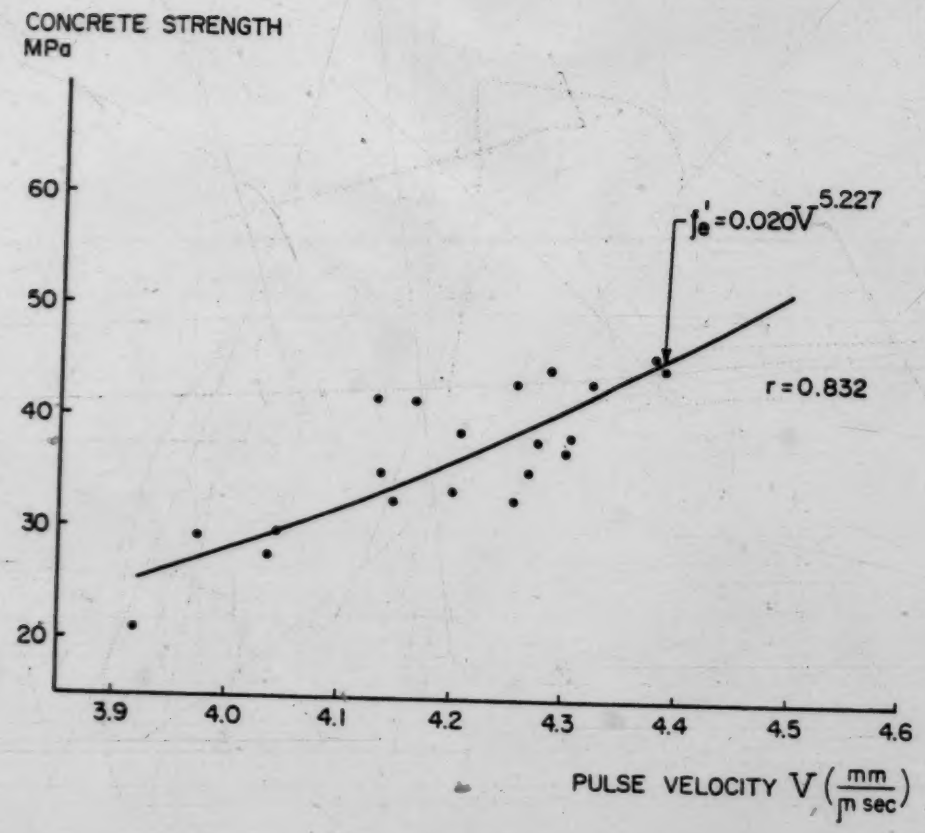


Fig. 5.1 Scatter Diagram and the Best Fitting Curve $f'_e = 0.020V^{5.227}$ for the Data on 20 Cores

$= 0.020V^{5.227}$ fitting the scatter diagram of pulse velocity vs. compressive strength.

5.3 Correlation Between Rebound Numbers and Concrete Strength

For each core location, 9 rebound readings were obtained in-situ as described in Chapter 4. The same 20 cores as in the previous analysis were used to correlate the minimum, mean and maximum rebound numbers with concrete strength. In these cases only the power curve model was used, i.e.

$$Y = bX^a$$

where X = rebound number (minimum, mean or maximum)

Y = compressive strength of concrete (MPa)

The results of the analysis are given in Tables 5.2, 5.3 and 5.4.

The values of correlation coefficients are 0.504, 0.127 and 0.040 respectively for minimum, mean and maximum rebound numbers vs. concrete strength relationships.

According to the table given by Storm (30) and shown in Appendix C as Table C1, the largest random value of the correlation coefficient at 5% significance level and m = (20-1) = 19 degrees of freedom is 0.432, which is less than 0.504 for the relationship given by the power curve f_e =

Table 5.2 Regression Analysis for Compressive Strength Versus Minimum Rebound Number: $f'_e = bR^a_{min}$

No.	Core Number	Random Variables		Results of Regression Analysis
		R_{min}	Core Compressive Strength MPa	f_e (1) MPa
1	2	3	4	5
1	AN#32W	35	43.42	37.00
2	CN#5W	31	32.56	33.10
3	CS#5E	33	38.93	35.05
4	BS#3E	33	29.42	35.05
5	CS#1E	42	45.76	43.75
6	AM#5W	33	43.33	35.05
7	AS#5E	43	41.82	44.71
8	AS#8E	37	37.34	38.94
9	AN#23W	28	38.04	30.14
10	BN#31W	34	33.49	36.03
11	DN#3E	32	35.28	34.08
12	ES#29W	31	27.51	33.10
13	EN#8W	30	38.44	32.11
14	DS#4E	36	44.74	37.97
15	AN#29W	39	44.74	40.87
16	CN#1W	31	21.07	33.10
17	EN#8E	36	41.65	37.97
18	BS#7E	34	32.56	36.03
19	DS#31E	32	35.16	34.08
20	ES#23W	35	29.79	37.00
Mean			$\bar{f}'_c$ =36.75	$\bar{f}_e$=36.26
Standard Deviation			σ=6.648	σ_e=3.710

Note: (1) $f_e = bR^a_{min} = 1.410\ R^{0.919}_{min}$

Correlation Coefficient r = 0.504

Table 5.3 Regression Analysis for Compressive Strength Versus Mean Rebound Number: $f'_e = bR^a_{mean}$ (1)

No.	Core Number	Random Variables	
		R_{mean}	Core Compressive Strength MPa
1	2	3	4
1	AN#32W	42.6	43.42
2	CN#5W	43.9	32.56
3	CS#5E	39.6	38.93
4	BS#3E	38.8	29.42
5	CS#1E	47.0	45.76
6	AM#5W	40.2	43.33
7	AS#5E	36.2	41.82
8	AS#8E	42.9	37.34
9	AN#23W	37.1	38.04
10	BN#31W	42.2	33.49
11	DN#3E	39.8	35.28
12	ES#29W	40.9	27.51
13	EN#8W	40.1	38.44
14	DS#4E	44.6	44.74
15	AN#29W	45.9	44.74
16	CN#1W	41.9	21.07
17	EN#8E	40.6	41.65
18	BS#7E	39.2	32.56
19	DS#31E	45.1	35.16
20	ES#23W	43.5	29.79

Note: (1) $f'_e = bR^a_{mean} = 9.351R^{0.363}_{mean}$

Correlation coefficient r = 0.127

Table 5.4 Regression Analysis for Compressive Strength Versus Maximum Rebound Number: $f'_e = bR^a_{max}$ (1)

No.	Core Number	Random Variables	
		R_{max}	Core Compressive Strength MPa
1	2	3	4
1	AN#32W	52	43.42
2	CN#5W	52	32.56
3	CS#5E	48	38.93
4	BS#3E	45	29.42
5	CS#1E	50	45.76
6	AM#5W	50	43.33
7	AS#5E	51	41.82
8	AS#8E	49	37.34
9	AN#23W	47	38.04
10	BN#31W	50	33.49
11	DN#3E	50	35.28
12	ES#29W	53	27.51
13	EN#8W	45	38.44
14	DS#4E	52	44.74
15	AN#29W	51	44.74
16	CN#1W	49	21.07
17	EN#8E	44	41.65
18	BS#7E	43	32.56
19	DS#31E	54	35.16
20	ES#23W	52	29.79

Note: (1) $f'_e = bR^a_{max} = 22.510R^{0.121}_{max}$

Correlation Coefficient r = 0.040

$1.410R_{min}^{0.919}$, but larger than the correlation coefficients for the relationships involving R_{mean} and R_{max}.

Therefore the last two rebound characteristics are considered to be respectively very poorly correlated and not correlated at all with the compressive strength of concrete cores.

Fig. 5.2 shows the established relationship $f_e = 1.410R_{min}^{0.919}$ fitting the scatter diagram of minimum rebound numbers vs concrete compressive strength.

The values of the estimated compressive strength of concrete were calculated for R_{min} only and are shown in Table 5.2 as the "Results of Regression Analysis". The mean estimated value of compressive strength is 36.26 MPa or 1.3% smaller than the actual value of 36.75 MPa. The standard deviation is 3.710 MPa or 44.2% smaller than the actual standard deviation of the compressive strength of cores, which is equal to 6.648 MPa.

5.4 Correlation Between Pulse Velocity, Rebound Number and Concrete Strength

Data of the previous 20 cores were also used to investigate the relationship

$$f'_c = a_o V^{a_1} R_{min}^{a_2}$$

In order to use linear regression analysis the above equation was rewritten as

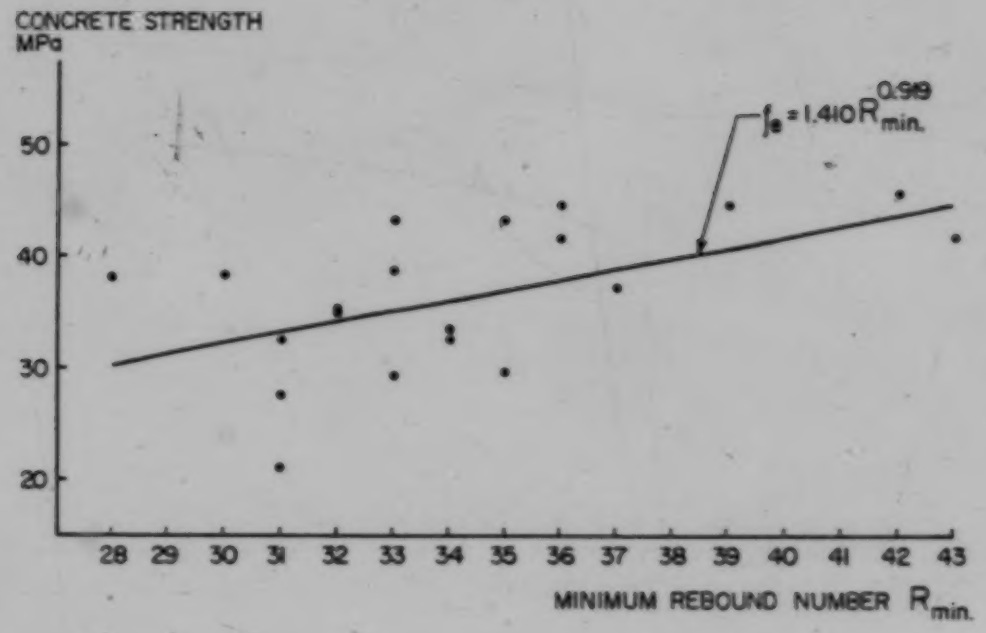


Fig. 5.2 Scatter Diagram and the Best Fitting Curve $f_e = 2.410 R_{min}^{0.919}$ for the Data on 20 Cores

$$\ell_n f'_c = \ell_n a_o + a_1 \ell_n V + a_2 \ell_n R_{min}$$

i.e. instead of using f'_c, V and R_{min}, a multiple linear regression analysis was done on $\ell_n f'_c$, $\ell_n V$ and $\ell_n R_{min}$. The results of the analysis are shown in Table 5.5. The relationship between concrete strength, pulse velocity and minimum rebound number is

$$f_e = 0.0045V^{4.707}R_{min}^{0.635}$$

In comparison with the relationship $f_e = 0.020V^{5.227}$ the correlation coefficient has improved from r = 0.832 to r = 0.896, which indicates that the correlation is very strong. The mean value of the estimated concrete strength is now equal 36.65 MPa, which is only 0.3% smaller than the actual compressive strength of cores. The standard deviation is equal to 6.329 MPa which is 4.8% smaller than the standard deviation of the compressive strength of cores.

5.5 Relationship Proposed by Samarin and Dhir (22)

Samarin and Dhir proposed the correlation formula

$$f'_c = A_o + A_1 R_{mean} + A_2 R^4$$

in vieu of the poor correlation established in Section 5.3. For f'_c vs R_{mean}, the last parameter was substituted by

Table 5.5 Regression Analysis for Compressive Strength Versus Pulse Velocity and Minimum Rebound Number:

$$f_e = a_o V^{a_1} R_{min}^{a_2}$$

No.	Core Number	V $\frac{mm}{\mu sec}$	ln V	R_{min}	ln R_{min}	f'_c MPa	ln f'_c	f_e(1) MPa
1	OLIX#32W	4.256	1.448	35	3.555	43.42	3.771	39.15
2	OLIIIX#5W	4.256	1.448	31	3.434	32.56	3.483	36.26
3	OLIIIZ#5E	4.204	1.436	33	3.496	38.93	3.662	35.64
4	OLIIZ#3E	3.972	1.379	33	3.496	29.42	3.382	27.26
5	OLIIIZ#1E	4.381	1.477	42	3.738	45.76	3.823	50.40
6	OLIY#9W	4.326	1.465	33	3.496	43.33	3.769	40.85
7	OLIZ#5E	4.129	1.418	43	3.761	41.82	3.733	38.74
8	OLIZ#8E	4.299	1.458	37	3.611	37.34	3.620	42.52
9	OLIX#23W	4.274	1.453	28	3.332	38.04	3.639	34.79
10	OLIIX#31W	4.195	1.434	34	3.526	33.49	3.511	35.99
11	OLIVX#3E	4.268	1.451	32	3.466	35.28	3.563	37.53
12	OLVZ#29W	4.035	1.395	31	3.434	27.51	3.315	28.25
13	OLVX#8W	4.304	1.460	30	3.434	38.44	3.649	38.36
14	OLIVZ#4E	4.388	1.479	36	3.584	44.74	3.801	46.14
15	OLIX#29W	4.286	1.455	39	3.664	44.74	3.801	43.36
16	OLIIIX#1W	3.917	1.365	31	3.434	21.07	3.048	24.54
17	OLVX#8E	4.164	1.426	36	3.584	41.65	3.729	35.96
18	OLIIZ#7E	4.148	1.423	34	3.526	32.56	3.483	34.17
19	OLIVZ#31E	4.134	1.419	32	3.466	35.16	3.560	32.28
20	OLVZ#23W	4.044	1.397	35	3.555	29.79	3.394	30.79
	Mean					$\bar{f}'_c$=36.75		$\bar{f}_e$=36.65
	Standard Deviation					$\hat{\sigma}$=6.648		$\hat{\sigma}_e$=6.329

Note: (1) $f_e = a_o V^{a_1} R_{min}^{a_2} = 0.0045\ V^{4.707}\ R_{min}^{0.635}$

Coefficient of Correlation r = 0.896

R_{min}. The results of the regression analysis are given in Table 5.6. The expression for the estimated concrete strength is

$$f_e = -25.6 + 0.655R_{min} + 0.128V^4$$

The coefficient of correlation r = 0.892. The mean estimated value of the compressive strength of cores is 36.75 MPa, i.e. the same as the actual. The standard deviation of the estimated concrete strength is 5.934 MPa, 10.7% smaller than the actual value.

5.6 Pulse Velocity and Concrete Density vs. Concrete Strength

The regression analysis was performed on the relationship

$$f'_c = a_o V^{a_1} \rho^{a_2} ,$$

using the same approach as in Section 4. The results are shown in Table 5.7. The expression for the estimated strength of concrete is given as

$$f_e = 0.0283V^{5.320}\rho^{-0.562}$$

The correlation coefficient has not improved in comparison with the relationship $f'_e = a_o V^{a_1}$, and remains r = 0.832.

Table 5.6 Regression Analysis for Compressive Strength Versus Pulse Velocity and Minimum Rebound Number: $f_e = A_o + A_1 R_{min} + A_2 V^4$

No.	Core Number	R_{min}	V^4	Core Compressive Strength MPa	f_e (1) MPa
1	2	3	4	5	6
1	AN#32W	35	328.100	43.42	39.23
2	CN#5W	31	328.100	32.56	36.61
3	CS#5E	33	312.357	38.93	35.91
4	BS#3E	33	248.907	29.42	27.80
5	CS#1E	42	368.377	45.76	48.96
6	AM#5W	33	350.224	43.33	40.74
7	AS#5E	43	290.656	41.82	39.68
8	AS#8E	37	341.562	37.34	42.26
9	AN#23W	28	333.686	38.04	35.36
10	BN#31W	34	309.690	33.49	36.22
11	DN#3E	32	331.816	35.28	37.74
12	ES#29W	31	265.078	27.51	28.56
13	EN#8W	30	343.154	38.44	37.88
14	DS#4E	36	370.737	44.74	45.33
15	AN#29W	39	337.449	44.74	43.04
16	DN#1W	31	235.404	21.07	24.77
17	EN#8E	36	300.637	41.65	36.37
18	BS#7E	34	296.043	32.56	34.48
19	DS#31E	32	292.066	35.16	32.66
20	ES#23W	35	267.451	29.79	31.48
	Mean			$\bar{f}'_c$=36.75	$\bar{f}_e$=36.75
	Standard Deviation			σ=6.648	σ_e=5.934

Note: (1) $f_e = A_o + A_1 R_{min} + A_2 V^4 =$

$= -25.6 + 0.655\ R_{min} + 0.128\ V^4$

Coefficient of Correlation r = 0.892

Table 5.7 Regression Analysis for Compressive Strength Versus Pulse Velocity and Density: $f_e = a_o V^{a_1} \rho^{a_2}$

No.	Core Number	V $\frac{mm}{\mu sec}$	ln V	ρ $\frac{T}{M^3}$	ln ρ	f'_c MPa	ln f'_c	f_e (1) MPa
1	2	3	4	5	6	7	8	9
1	AN#32W	4.256	1.448	2.320	0.842	43.42	3.771	37.56
2	CN#5W	4.256	1.448	2.376	0.865	32.56	3.483	37.44
3	CS#5E	4.204	1.436	2.351	0.855	38.93	3.662	36.30
4	BS#3E	3.972	1.379	2.306	0.836	29.42	3.382	31.51
5	CS#1E	4.381	1.477	2.386	0.870	45.76	3.823	40.26
6	AM#9W	4.326	1.465	2.305	0.835	43.33	3.769	39.06
7	AS#5E	4.129	1.418	2.345	0.852	41.82	3.733	34.74
8	AS#8E	4.299	1.458	2.333	0.847	37.34	3.620	38.39
9	AN#23W	4.274	1.453	2.354	0.856	38.04	3.639	37.80
10	BN#31W	4.195	1.434	2.378	0.866	33.49	3.511	35.70
11	DN#3E	4.268	1.451	2.359	0.858	35.28	3.563	37.72
12	ES#29W	4.035	1.395	2.269	0.819	27.51	3.315	32.79
13	EN#8W	4.304	1.460	2.338	0.849	38.44	3.649	38.58
14	DS#4E	4.388	1.479	2.386	0.870	44.74	3.801	40.40
15	AN#29W	4.286	1.455	2.340	0.850	44.74	3.801	38.10
16	CN#1W	3.917	1.365	2.313	0.839	21.07	3.048	30.43
17	EN#8E	4.164	1.426	2.342	0.851	41.65	3.729	35.44
18	BS#7E	4.148	1.423	2.324	0.843	32.56	3.483	35.10
19	DS#31E	4.134	1.419	2.358	0.858	35.16	3.560	34.82
20	ES#23W	4.044	1.397	2.362	0.860	29.79	3.394	32.90
						$\bar{f}_c$=36.75		$\bar{f}_e$=36.25
						$\hat{\sigma}_c$=6.648		$\hat{\sigma}_e$=2.795

Note: (1) $f_e = a_o V^{a_1} \rho^{a_2} = = 0.0283\ V^{5.320} \cdot \rho^{-0.562}$

Coefficient of correlation r = 0.832

The difference between the actual (36.75 MPa) and estimated (36.25 MPa) values of the means is 1.4%, the same as in f'_c vs. V case. But the standard deviation has changed significantly and is now 2.795 MPa, or 58% smaller than the actual value of 6.648 MPa.

5.7 Pulse Velocity, Minimum Rebound Number and Concrete Density vs. Concrete Strength

The analysed relationship was

$$f'_c = a_o V^{a_1} R_{min}^{a_2} \rho^{a_3} .$$

As the first variable the analysis involved the value of the estimated concrete strength calculated as $f_e = 0.0045V^{4.707}R_{min}^{0.635}$ and given in Table 5.5. The second variable was the concrete density ρ (T/m^3), and the third variable was f'_c (MPa). The results are shown in Table 5.8. The correlation coefficient has improved marginally from r = 0.896 for $f_e = 0.0045V^{4.707}R_{min}^{0.635}$ to r = 0.899 for $f_e = \frac{0.0097V^{4.971}R_{min}^{0.671}}{\rho^{1.501}}$; There was also slight improvement in the estimated standard deviation, which is now 6.365 MPa, or only 4.2% smaller than the actual value of 6.648 MPa, while the estimated standard deviation of the relationship $f_e = 0.0045V^{4.707}R_{min}^{0.635}$ is 4.8% smaller than the actual value.

Table 5.8 Regression Analysis for Compressive Strength Versus Pulse Velocity, Minimum Rebound Number and Density

$$f'_e = a_o f_e^{a_1} \rho^{a_2}$$

No.	Core Number	f'_e from Table 'Q' MPa	ln f_e	ρ $\frac{1}{M^3}$	ln ρ	f'_c CORE — MPa	ln f'_c	f'_e (1)
1	2	3	4	5	6	7	8	9
1	AN#32W	39.15	3.667	2.320	0.842	43.42	3.771	39.85
2	CN#5W	36.26	3.591	2.376	0.865	32.56	3.483	35.53
3	CS#5E	35.64	3.573	2.351	0.855	38.93	3.662	35.39
4	BS#3E	27.26	3.305	2.306	0.836	29.42	3.382	27.43
5	CS#1E	50.40	3.920	2.386	0.870	45.76	3.823	49.92
6	AM#9W	40.85	3.710	2.305	0.835	43.33	3.769	42.14
7	AS#5E	38.74	3.657	2.345	0.852	41.82	3.733	38.85
8	AS#8E	42.52	3.750	2.333	0.847	37.34	3.620	43.18
9	AN#23W	34.79	3.549	2.354	0.856	38.04	3.639	34.45
10	BN#31W	35.99	3.583	2.378	0.866	33.49	3.511	35.18
11	DM#3E	37.53	3.625	2.359	0.858	35.28	3.563	37.22
12	ES#29W	28.25	3.341	2.269	0.819	27.51	3.315	29.23
13	EN#8W	38.36	3.647	2.338	0.849	38.44	3.649	38.61
14	DS#4E	46.14	3.832	2.386	0.870	44.74	3.801	45.49
15	AN#29W	43.36	3.770	2.340	0.850	44.74	3.801	43.90
16	CN#1W	24.54	3.200	2.313	0.838	21.07	3.048	24.48
17	EN#8E	35.96	3.582	2.342	0.851	41.65	3.729	35.94
18	BS#7E	34.17	3.531	2.324	0.843	32.56	3.483	34.47
19	DS#31E	32.28	3.474	2.354	0.859	35.16	2.560	31.63
20	ES#23W	30.79	3.428	2.362	0.860	29.79	2.394	30.13

$\bar{f}_c$=36.75 $\hat{\sigma}$=6.648 $\bar{f}'_e$=36.65 $\hat{\sigma}'_c$=6.365

Note: (1) $f'_e = \dfrac{0.0097\ V^{4.971}\ R_{min}^{0.671}}{\rho^{1.501}}$

Coefficient of Correlation r = 0.899

5.8 Graphical Comparison of the Regression Formulas

The results of the regression analysis are shown in Figs. 5.3, 5.4, 5.5 and 5.6. The estimated values of concrete strength are plotted vs. compressive strength of cores for the relationships

$$f_e = 1.41R_{min}^{0.919} \; ; \; r = 0.504$$

$$f_e = 0.020V^{5.227} \; ; \; r = 0.832$$

$$f_e = -25.599 + 0.6549R_{min} + 0.1277V^4 \; ; \; r = 0.892$$

$$f_e = 0.0045V^{4.707}R_{min}^{0.635} \; ; \; r = 0.896.$$

The figures are placed in the order of the improvement of the correlation coefficient. The scatter of data is compared with ± 15% dispersion from the perfect fit given by a straight line $f_c' = f_e$. Figure 5.3 shows that only 11 of 20 points i.e. 55% lie within the ± 15% boundaries. Fig. 5.4 features 16 points or 80% within the same unit.

Fig. 5.4 and Fig. 5.5 both indicate that 19 points lie within ± 15% limit from the perfect line, which is 95% of the group. It is a significant improvement if compared with the relationship involving only one independent variable V, and even more so for the relationship involving only R_{min}. Further analysis should tell whether the "combined method" can produce an improvement of correlation on a small group of cores, say on 6 cores.

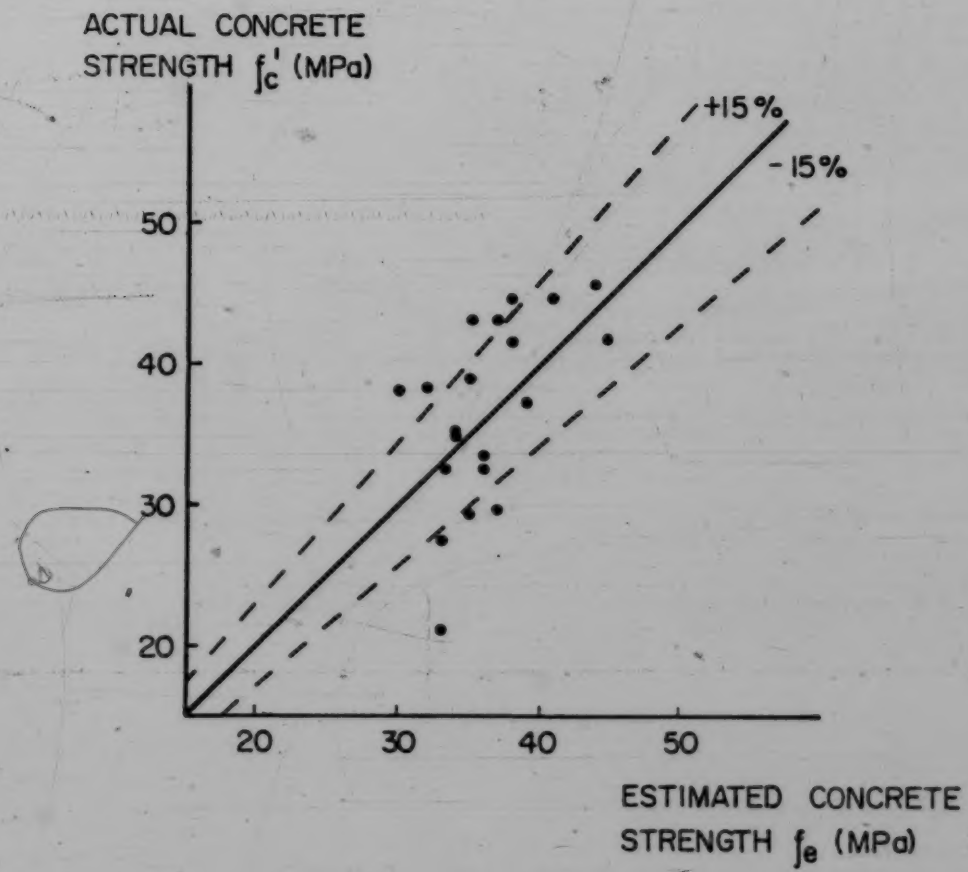


Fig. 5.3 Correlation Between the Actual and the Estimated Concrete Strength for the Relationship $f_e = 1.410R_{min}^{0.919}$ ($r = 0.504$) Based on the Data of 20 Cores

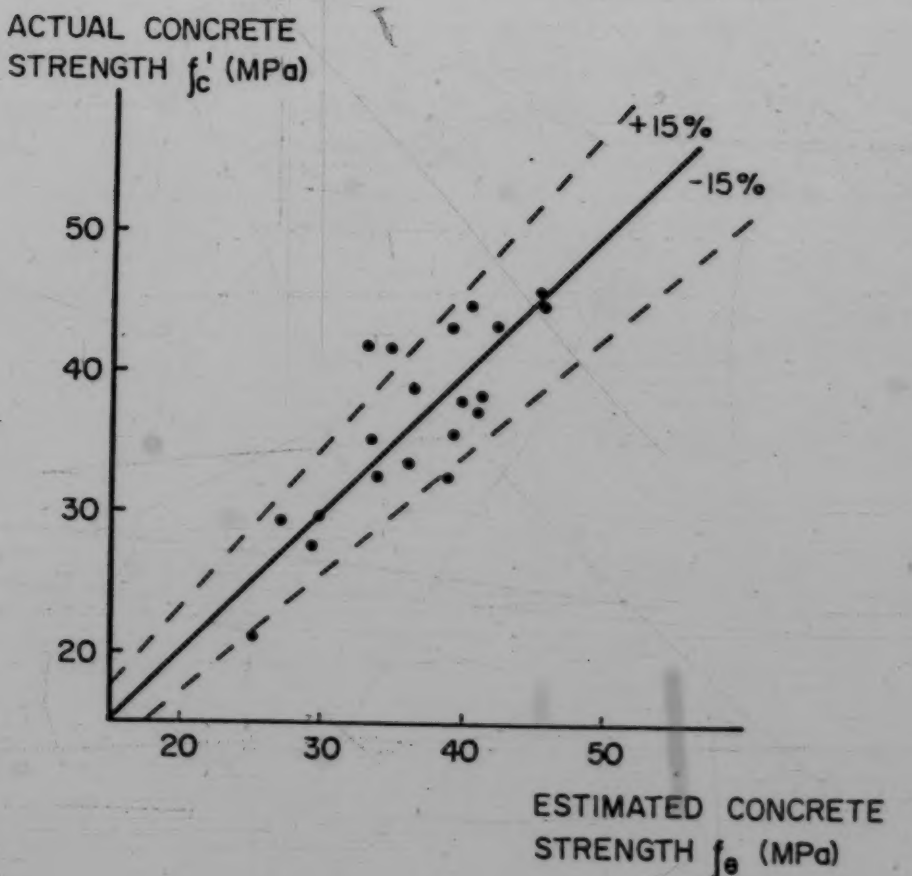


Fig. 5.4 Correlation Between the Actual and the Estimated Concrete Strength for the Relationship $f_e' = 0.020V^{5.227}$ (r = 0.832) Based on the Data of 20 Cores

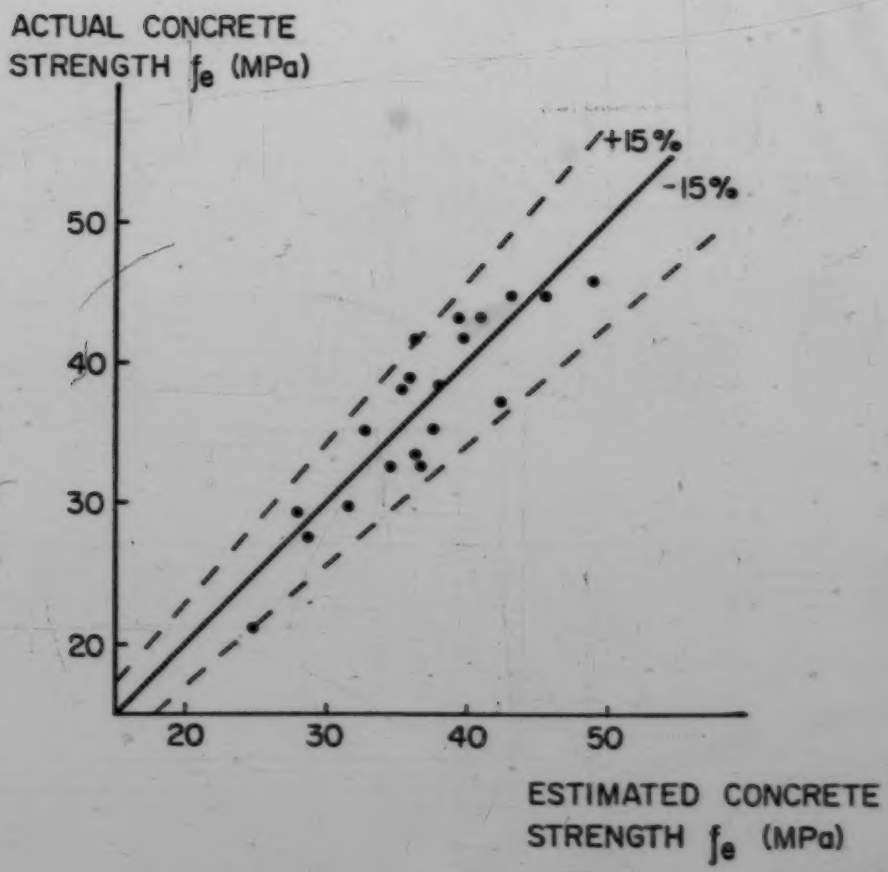


Fig. 5.5 Correlation Between the Actual and the Estimated Concrete Strength for the Relationship $f_e = -25.599 + 0.6549R_{min} + 0.1277V^4$ ($r = 0.892$) Based on the Data of 20 Cores

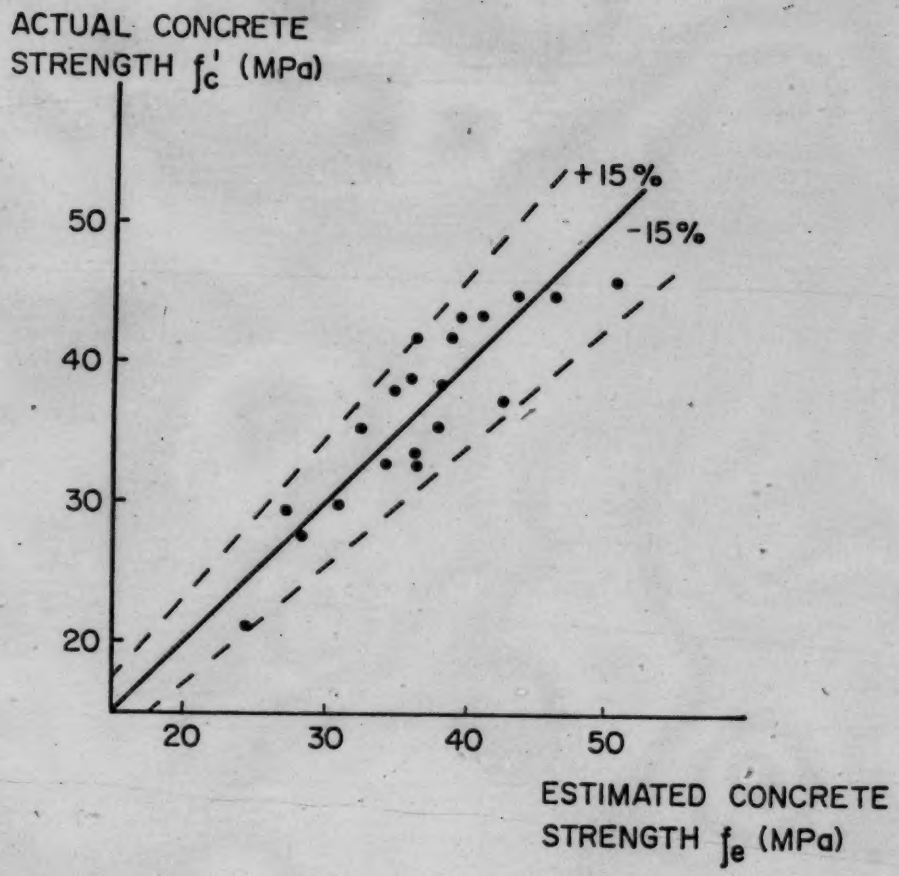


Fig. 5.6 Correlation Between the Actual and the Estimated Concrete Strength for the Relationship $f_e = 0.0045V^{4.707}R_{min}^{0.635}$ (r = 0.896) Based on the Data of 20 Cores

6. PREDICTION OF THE MEAN CONCRETE STRENGTH BASED ON NON-DESTRUCTIVE TESTS AND CORES

6.1 Introduction

As long as any testing involves a limited number of samples from a population there is always a need to transform statistical characteristics of the sample into statistical characteristics of the population. And whenever statistical characteristics of the sample are obtained by an indirect method, as is the case with evaluation of concrete strength through non-destructive tests, these transformations must also take into account the correlation of indirect methods with direct observations. The reliability of resulting parameters thus obtained is defined by so-called confidence limits.

This chapter presents statistical bases and examples of an approach to the estimation of mean concrete strength in an existing structure within prescribed confidence limits, based on limited sampling of core strength and nondestructive tests.

Correlation curves used in examples of this chapter were obtained in Chapter 5.

6.2 Relationships Between Statistical Parameters of Samples and Populations

The statistical parameters obtained in this study are (8):

$$\bar{x} = \text{sample mean} = \frac{\sum_{i=n}^{1} x_i}{n} \; ; \qquad (6.1)$$

$$\hat{\sigma} = \text{sample standard deviation} = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}} \qquad (6.2)$$

$$\hat{v} = \text{sample coefficient of variation} = \frac{\hat{\sigma}}{\bar{x}} \; ; \qquad (6.3)$$

x_i = random observation;

n = number of observations.

The parameters of the population represented by the samples are:

μ = population mean;

σ = population standard deviation

v = population coefficient of variation = $\frac{\sigma}{\mu}$

Relationships between the sample and population parameters are given by the theory of confidence limits (3,29).

$$\mu = \bar{x} \pm t_{\alpha,m} \frac{\hat{\sigma}}{\sqrt{n}} \qquad (6.4)$$

and

$$\sigma = \hat{\sigma} \pm t_{\alpha,m} \frac{\hat{\sigma}}{\sqrt{2n}} \qquad (6.5)$$

$$v = \hat{v} \pm t_{\alpha,m} \frac{\hat{v}}{\sqrt{2n}} \qquad (6.6)$$

where $t_{\alpha,m}$ = random variable of the Student's t distribution at confidence limit α for a sample with m = n-1 degrees of freedom.

Table C2 for percentile values $t_{\alpha,m}$ for Student's t distribution with m = n-1 degrees of freedom is given in Appendix C for both the two-tailed and one-tailed tests(30).

When concrete strength parameters are obtained through non-destructive tests and calibration curves, the expressions for $\hat{\sigma}$ are modified as follows(23):

$$\hat{\sigma}^2 = \hat{\sigma}_{et}^2 = \hat{\sigma}_e^2 + \hat{\sigma}_t^2 \qquad (6.7)$$

where $\hat{\sigma}_{et}$ = total standard deviation of sample

$\hat{\sigma}_e$ = sample standard deviation of estimated concrete strength obtained from calibration curves

$\hat{\sigma}_t$ = sample standard error of the test method,

$$= \sqrt{\frac{\sum_{i=1}^{n} (f_{ie} - \bar{f}_e)^2}{n_1 - 1}}$$

σ_t = standard error of the calibration curve as given in [28]

$$= \sqrt{\frac{\sum_{j=1}^{n_2} (f'_{jc} - f_{je})^2}{n_2 - 2}}$$

where f_{ie} = value of concrete strength of sample i estimated using a calibration curve

$\bar{f}_e$ = mean value of estimated concrete strength of n_1 samples

n_1 = size of the sample involved in nondestructive test

f'_{jc} = test value of concrete strength of sample j

f_{je} = value of concrete strength of sample j estimated using calibration curve

n_2 = size of the sample used for calibration

In formula (6.7) σ_e and σ_t represent samples of equal size.

From a known population standard error a sample standard error for a desired sample size can be calculated from the formula

$$\hat{\sigma}^s_t = \frac{\sigma_t}{\left(1 + \frac{t_{\alpha,m}}{\sqrt{2n}}\right)} \qquad (6.8)$$

which is derived from formula (6.5).

6.3 Calculation of the Mean Concrete Strength of the Population from Tests on 31 Cores

The compressive test results on 31 cores are given in

Table 6.1 and plotted as histogram in Appendix A in Fig. A20. The mean value of the compressive strength of cores is $\bar{x}$ = 36.83 MPa, the standard deviation is $\hat{\sigma}$ = 6.58 MPa, the coefficient of variation is 0.179.

The mean concrete strength of the population is calculated by formula (6.4)

$$\mu = 36.83 \pm t_{\alpha,m} \frac{6.58}{\sqrt{31}}$$

where α = 95%

m = 31 - 1 = 30

$t_{\alpha,m}$ = 2.04 (Table C1, two tailed test)

$$\mu = 36.83 \pm 2.04 \frac{6.58}{\sqrt{31}} = 36.83 \pm 2.41$$

$$\mu' = 36.83 - 2.41 = 34.42 \text{ MPa}$$

$$\mu'' = 36.83 + 2.41 = 39.24 \text{ MPa}$$

The standard deviation of the population is calculated by formula (6.5)

$$\sigma = 6.58 \pm 2.04 \frac{6.58}{\sqrt{2 \times 31}} = 6.58 \pm 1.70$$

$$\sigma' = 6.58 - 1.70 = 4.88 \text{ MPa}$$

$$\sigma'' = 6.58 + 1.70 = 8.28 \text{ MPa}$$

Coefficients of variation v for $t_{\alpha,m} = t_{95\%,30} = 2.04$

Table 6.1 Compressive Strength of 31 Cores

No.	Core Number	f'_{ic} MPa
1	2	3
1	AN#32W	43.42
2	CN#5W	32.56
3	CS#5E	38.93
4	BS#3E	29.42
5	CS#1E	45.76
6	AM#9W	43.33
7	AS#5E	41.82
8	AS#8E	37.34
9	AN#23W	38.04
10	BN#31W	33.49
11	DN#3E	35.28
12	ES#29W	27.51
13	EN#8W	38.44
14	DS#4E	44.74
15	AN#29W	44.74
16	CN#1W	21.07
17	EN#8E	41.65
18	BS#7E	32.56
19	DS#31E	35.16
20	ES#23W	29.79
21	AN#32E	36.77
22	CN#5E	34.34
23	AM#9E	36.07
24	AN#23E	33.73
25	BN#31E	47.95
26	DN#3W	37.31
27	AN#29E	44.09
28	CN#1E	20.33
29	BN#8W	35.62
30	BN#8E	37.28
31	BN#4W	37.25

Mean $\bar{x}_c = 36.83$

Standard Deviation = $\hat{\sigma}_c = 6.582$

Coefficient of variation $\hat{v}_c = 0.179$

$$v = \hat{v} \pm 2.04 \frac{\hat{v}}{\sqrt{2 \times 31}} = 0.179 \pm 2.04 \frac{0.179}{\sqrt{62}}$$
$$= 0.179 \pm 0.046$$

$v' = 0.133$

$v'' = 0.225$

$0.133 < v < 0.225$

6.4 Calculation of the Mean Concrete Strength of the Population From Pulse Velocities of 31 Cores Based on Calibration Curve From 20 Cores

The regression curve $f_e = 0.020V^{5.227}$ obtained in Section 5.2 from pulse velocities and compressive strength of 20 cores was used as a calibration curve in this estimate. Table 6.2 shows the calculation of the standard error for the calibration curve, i.e. $\hat{\sigma}_t = 4.259$ MPa.

Table 6.2 gives the estimated concrete strength based on pulse velocities of 31 cores and calibration curve $f_e = 0.020V^{5.227}$. The estimated sample mean of concrete strength is $\bar{x}_e = 35.94$ MPa with a standard deviation $\hat{\sigma}_e = 6.042$ MPa. From formula (6.5) with $t_{95\%,19} = 2.09$

$$\sigma_t = 4.259 \pm 2.09 \frac{4.259}{\sqrt{2 \times 20}} = 4.259 \pm 1.407$$

Accepting the upper limit value $\sigma_t'' = 4.259 + 1.407 = 5.666$ (MPa) for 31 samples from formula (6.8)

$$\hat{\sigma}_t^s = \frac{\sigma_t'}{\left(1 + \frac{t_{95\%,30}}{\sqrt{2 \times 31}}\right)} = \frac{5.666}{\left(1 + \frac{2.04}{\sqrt{2 \times 31}}\right)} = 4.500 \text{ (MPa)}$$

Table 6.2 Calculation of Standard Error of the Calibration Curve $f_e = 0.020V^{5.227}$

No.	Core Number	f'_{jc} MPa	$f_{je}=0.020V^{5.227}$ MPa	$(f'_{jc}-f_{je})^2$
1	AN#32W	43.42	38.80	21.34
2	CN#5W	32.56	38.80	38.94
3	CS#5E	38.93	36.39	6.45
4	BS#3E	29.42	27.04	5.66
5	CS#1E	45.76	45.14	0.38
6	AM#9W	43.33	42.25	1.17
7	AS#5E	41.82	33.12	75.69
8	AS#8E	37.34	40.89	12.60
9	AN#23W	38.04	39.66	2.62
10	BN#31W	33.49	35.98	6.20
11	DN#3E	35.28	39.37	16.73
12	ES#29W	27.51	29.36	3.42
13	EN#8W	38.44	41.14	7.29
14	DS#4E	44.74	45.52	0.61
15	AN#29W	44.74	40.25	20.16
16	CN#1W	21.07	25.14	16.56
17	EN#8E	41.65	34.61	49.56
18	BS#7E	32.56	33.92	1.85
19	DS#31E	35.16	33.33	3.35
20	ES#23W	29.79	23.80	35.88

Mean $\bar{x}_e = 35.94$ $\quad \Sigma\ 326.46$

Standard Deviation $\hat{\sigma}_e = 6.042$

$$\hat{\sigma}_t = \sqrt{\frac{\Sigma(f'_{jc} - f_{je})^2}{n - 2}} = \sqrt{\frac{326.46}{20 - 2}} = 4.259 \text{ (MPa)}$$

From formula (6.7)

$$\hat{\sigma}_{et}^{\,2} = \hat{\sigma}_{e}^{\,2} + \hat{\sigma}_{t}^{s2} = (6.042)^2 + (4.500)^2 = 56.76$$

$$\hat{\sigma}_{et} = 7.534 \text{ (MPa)}$$

From formula (6.4)

$$\mu_{NDT} = 35.94 \pm 2.04 \frac{7.534}{\sqrt{31}} = 35.94 \pm 2.76$$

Accepting the lower limit value of μ_{NDT}:

$$\mu'_{NDT} = 35.94 - 2.76 = 33.18 \text{ (MPa)}$$

Sample Coefficient of variation: $\hat{v} = \frac{7.534}{35.94} = 0.210$

From formula (6.6) population coefficient of population is:

$$v = 0.210 \pm 2.04 \frac{0.210}{\sqrt{2 \times 31}} = 0.210 \pm 0.054$$

Accepting the upper limit value:

$$v' = 0.210 + 0.054 = 0.264.$$

The lower boundary mean concrete strength of the population

based on the compressive strength of 31 cores is $\mu' = 34.42$ MPa. Hence the error of the method in comparison with results on 31 cores is:

$$\Delta'_{NDT} = \frac{34.42 - 33.25}{34.42} \times 100\% = 3.40\%$$

6.5 Calculation of the Mean Concrete Strength of the Population from Pulse Velocities of 31 Cores Based on Calibration Curve from 6 Cores

The 6 cores used for calibration were selected from 31 cores given in Table 6.3. The pulse velocity of each core represents one cell of a 6-cell histogram similar to the one shown in Fig. 6.1 but based on in-situ velocities at the locations of the mentioned 31 cores.

Data on the 6 cores selected are given in Table 6.4. The expression for the regression curve based on 6 cores is $f_e = 0.00172V^{6.957}$. This curve will be used as the calibration curve. The standard error of calibration is $\hat{\sigma}_t = 4.404$ (MPa). The estimated concrete strengths involving pulse velocities of 31 cores are given in Table 6.5.

The estimated sample mean of concrete strength is $\bar{x}_e = 37.35$ MPa with a standard deviation of $\hat{\sigma}_e = 7.739$ MPa. From formula (6.5) with $t_{95\%,5} = 2.57$

$$\sigma_t = 4.404 \pm 2.57 \frac{4.404}{\sqrt{2 \times 6}} \pm 3.267$$

Table 6.3 Calculation of the Mean Concrete Strength from Velocities of 31 Cores Based on Calibration Curve from 20 Cores

No.	Core Number	V $\frac{mm}{\mu sec}$	f'_{ic} MPa	$f_e=0.020V^{5.227}$ MPa
1	2	3	4	5
1	AN#32W	4.256	43.42	38.80
2	CN#5W	4.256	32.56	38.80
3	CS#5E	4.204	38.93	36.39
4	BS#3E	3.972	29.42	27.04
5	CS#1E	4.381	45.76	45.14
6	AM#9W	4.326	43.33	42.25
7	AS#5E	4.129	41.82	33.12
8	AS#8E	4.299	37.34	40.89
9	AN#23W	4.274	38.04	39.66
10	BN#31W	4.195	33.49	35.98
11	DN#3E	4.268	35.28	39.37
12	ES#29W	4.035	27.51	29.36
13	EN#8W	4.304	38.44	41.14
14	DS#4E	4.388	44.74	45.52
15	AN#29W	4.286	44.74	40.25
16	CN#1W	3.917	21.07	25.14
17	EN#8E	4.164	41.65	34.61
18	BS#7E	4.148	32.56	33.92
19	DS#31E	4.134	35.16	33.33
20	ES#23W	4.044	29.79	23.80
21	AN#32E	4.293	36.77	40.65
22	CN#5E	4.263	34.34	39.19
23	AM#9E	4.120	36.07	32.78
24	AN#23E	3.993	33.73	27.84
25	BN#31E	4.326	47.95	42.31
26	DN#3W	4.147	37.31	33.92
27	AN#29E	4.337	44.09	42.87
28	CN#1E	3.920	20.33	25.28
29	BN#8W	4.136	35.62	33.46
30	BN#8E	4.084	37.28	31.32
31	BN#4W	4.242	37.25	40.11
Mean			$\bar{f}_c$ = 36.83	$\bar{f}_e$=35.94
Standard Deviation			$\hat{\sigma}_e$ = 6.582	$\hat{\sigma}_e$=6.042

Table 6.4 Calibration on 6 Cores vs f'_c, and Calculation of Standard Error

No.	Core Number	V_{core} $\frac{mm}{\mu sec}$	f'_{jc} MPa	f_{je} (1) MPa	$(f'_{jc} - f_{je})^2$
1	2	3	4	5	6
1	CN#1W	3.917	21.07	22.99	3.69
2	EN#8E	4.164	41.65	35.18	41.86
3	ES#23W	4.044	29.79	28.71	1.17
4	BN#4W	4.242	37.25	40.03	7.73
5	BN#31E	4.326	47.95	45.88	4.28
6	CS#1E	4.381	45.76	50.10	18.84
					Σ 77.57

Note: (1) $f_e = 0.00172V^{6.957}$

$r = 0.944$

$$\hat{\sigma}_t = \sqrt{\frac{(f'_{jc} - f_{je})^2}{n - 2}} = \sqrt{\frac{77.57}{4}} = 4.404 \text{ (MPa)}$$

Table 6.5 Estimated Concrete Strength from Calibration on 6 Cores Involving Pulse Velocities and Concrete Strength

No.	Core Number	V $\frac{mm}{\mu sec}$	f'_{ic} MPa	$f_{ie}=0.00172V^{6.957}$
1	AN#32W	4.256	43.42	40.96
2	CN#5W	4.256	32.56	40.96
3	CS#5E	4.204	38.93	37.60
4	BS#3E	3.972	29.42	25.33
5	CS#1E	4.381	45.76	50.10
6	AM#9W	4.326	43.33	45.88
7	AS#5E	4.129	41.82	33.18
8	AS#8E	4.299	37.34	43.93
9	AN#23W	4.274	38.04	42.18
10	BN#31W	4.274	33.49	42.18
11	DN#3E	4.268	35.28	41.77
12	ES#29W	4.035	27.51	28.26
13	EN#8W	4.304	38.44	44.28
14	DS#4E	4.388	44.74	50.66
15	AN#29W	4.286	44.74	43.01
16	CN#1W	3.917	21.07	22.99
17	EN#8E	4.164	41.65	35.18
18	BS#7E	4.148	32.56	34.25
19	DS#31E	4.134	35.16	33.46
20	ES#23W	4.044	29.79	28.71
21	AN#32E	4.293	36.77	43.50
22	CN#5E	4.263	34.34	41.43
23	AM#9E	4.120	36.07	32.68
24	AN#23E	3.993	33.73	26.28
25	BN#31E	4.326	47.95	45.88
26	DN#3W	4.147	37.31	34.20
27	AN#29E	4.337	44.09	46.70
28	CN#1E	3.920	20.33	23.11
29	BN#8E	4.136	35.62	33.57
30	BN#8E	4.084	37.28	30.74
31	BN#4W	4.242	37.25	40.03
Mean			$\bar{f}'_c=36.83$	$\bar{f}_e=37.35$
Standard Deviation			$\hat{\sigma}_c=6.582$	$\hat{\sigma}_e=7.739$

Accepting the upper limit value $\sigma_t'' = 4.404 + 3.267 = 7.671$ (MPa) from formula (6.8) with $t_{95\%,30} = 2.04$ (n = 31)

$$\hat{\sigma}_t^s = \frac{7.671}{\left(1 + \frac{2.04}{\sqrt{2 \times 31}}\right)} = 6.093, \text{ then}$$

$$\hat{\sigma}_{et} = \sqrt{\hat{\sigma}_e^2 + \hat{\sigma}_t^{s2}} = \sqrt{(7.739)^2 + (6.093)^2} = \sqrt{97.017}$$

$$\hat{\sigma}_{et} = 9.850 \text{ (MPa)}$$

From formula (6.9)

$$\mu_{NDT} = 37.35 \pm 2.04 \frac{9.850}{\sqrt{31}} = 37.35 \pm 3.61$$

Accepting the lower limit value of μ_{NDT}:

$$\mu'_{NDT} = 37.35 - 3.61 = 33.74 \text{ (MPa)}$$

Sample coefficient of variation: $\hat{v} = \frac{9.850}{37.35} = 0.264$

From formula (6.6) population coefficient of variation is:

$$v = 0.264 \pm 2.04 \frac{0.264}{\sqrt{2 \times 31}} = 0.264 \pm 0.068$$

Accepting the upper limit value v' = 0.264 + 0.068 = 0.332

Error of method in comparison with results on 31 cores:

$$\Delta' = \frac{34.42 - 33.74}{34.42} \times 100\% = 1.98\%$$

6.6 Calculation of the Mean Concrete Strength of the Population From Pulse Velocities and Minimum Rebound Numbers of 31 Cores Based on Calibration Curve from 6 Cores

The same 6 cores as in Section 6.5 were used. Data on 6 cores are given in Table 6.6. The expression for the regression curve involving pulse velocity and minimum rebound number is $f_e = 0.00203V^{5.238}R_{min}^{0.636}$. The sample standard error of calibration is $\hat{\sigma}_t = 4.157$ MPa.

The estimated concrete strengths from the calibration curve involving pulse velocities and minimum rebound numbers of 31 cores are given in Table 6.7. The estimated sample mean of concrete strength is $\bar{x}_e = 35.75$ MPa with a standard deviation $\hat{\sigma}_e = 6.384$ MPa.

From formula (6.5) with $t_{95\%,5} = 2.57$

$$\sigma_t = 4.157 \pm 2.57 \frac{4.157}{\sqrt{2 \times 6}} = 4.157 \pm 3.084$$

Accepting the upper limit value: $\sigma_t = 4.157 + 3.084 = 7.241$ (MPa)

From formula (6.8) for 31 samples

$$\sigma_t^s = \frac{7.241}{\left(1 + \frac{2.04}{\sqrt{2 \times 31}}\right)} = 5.751$$

$$\hat{\sigma}_{et}^2 = \sqrt{\hat{\sigma}_e^2 + \hat{\sigma}_t^{s2}} = \sqrt{(6.384)^2 + (5.751)^2} = 8.592 \text{ (MPa)}$$

From formula (6.4)

Table 6.6 Calibration on 6 Cores: V & R_{min} vs. f'_c

No.	Core Number	V_{CORE} $\frac{mm}{\mu sec}$	R_{min}	f'_{jc} MPa	f_{je} (1) MPa	$(f'_{ic} - f_{ie})^2$
1	CN#1W	3.917	31	21.07	22.96	3.57
2	EN#8E	4.164	36	41.65	34.78	47.20
3	ES#23W	4.044	35	29.79	29.31	0.23
4	BN#4W	4.242	36	37.25	38.33	1.17
5	BN#31E	4.326	43	47.95	47.56	0.15
6	CS#1E	4.381	42	45.96	50.06	16.81
						Σ 69.13

Note: (1) $f_{je} = 0.00203\ V^{4.238}\ R_{min}^{0.6360}$

$r = 0.948$

$\hat{\sigma}_t = \sqrt{\frac{69.13}{n-2}} = 4.157$

$n = 6$

Table 6.7 Calculation of the Ordinates of the Probability Density Function f(x) of the Normal Distribution with $\mu = 4.140$ mm/μsec and $\sigma = 0.152$ mm/μsec for the Pulse Velocities in 6 Cores; Calculation of Sizes of Simulated Groups

No.	Core Number	V $\frac{mm}{\mu sec}$	f(x)	$\frac{f(x)}{f(x)_{min}}$	Sizes of Simulated Groups
1	2	3	4	5	6
1	CN#1W	3.917	0.136	1.2	2
2	EN#8E	4.164	0.394	3.5	7
3	ES#23W	4.044	0.327	2.9	6
4	BN#4W	4.242	0.318	2.8	6
5	BN#31E	4.326	0.189	1.7	3
6	LS#1E	4.381	0.113	1.0	2

$$\mu_{NDT} = 35.75 \pm 2.04 \frac{8.592}{\sqrt{31}} = 35.75 \pm 3.15$$

Accepting the lower limit value of μ_{NDT}:

$$\mu'_{NDT} = 35.75 - 3.15 = 32.60 \text{ (MPa)}$$

Sample coefficient of variation $\hat{v} = 8.592/35.75 = 0.240$

Population coefficient of variation from formula (6.6)

$$v = 0.240 \pm 2.04 \frac{0.240}{\sqrt{2 \times 31}} = 0.240 \pm 0.062$$

Accepting the upper limit value of v

$$v'' = 0.240 + 0.062 = 0.302$$

Error of the method in comparison with results on 31 cores:

$$\Delta' = \frac{34.42 - 32.60}{34.42} \times 100\% = 5.28\%$$

6.7 Calculation of the Mean Concrete Strength of the Population from Pulse Velocities of 31 Cores and Calibration on 6 Simulated Groups Derived from 6 Cores

In this evaluation, each core of the 6 cores selected for calibration was replaced by a simulated group of cores, whose means of pulse velocities and compressive strengths were taken equal to the pulse velocity and compressive

strength of the given core. The size of each group was based on the assumption that pulse velocities of the concrete under investigation are normally distributed as shown in Fig. 4.1 and Fig. 6.1 with probability density function given by a mean μ and a standard deviation σ. Then for each group's mean pulse velocity a value of the standard normal density f(x) was calculated. Ratios between standard normal densities of simulated groups provided the ratios between group sizes. By assigning a convenient whole number to the size of the smallest group, sizes of the other groups are calculated.

Then a calibration curve is established through the regression analysis using the size and properties of each group. In formulas (6.4) and (6.5) number of degrees of freedom of the simulated sample is taken as $m = n^* - 1$. The value n^* is the sum of the number of original cores (6 in this case) and number of degrees of freedom (in this case 2, μ and σ) of the probability density function f(x) used to create the simulated groups.

Example

In order to establish a probability density function the mean pulse velocity and standard deviation of the population were calculated using formulas 6.4 and 6.5.

$$\mu_x = \bar{x} \pm t_{\alpha,m} \frac{\hat{\sigma}}{\sqrt{n}} \; ; \; \sigma_x = \hat{\sigma} \pm t_{\alpha,m} \frac{\hat{\sigma}}{\sqrt{2n}} \; ;$$

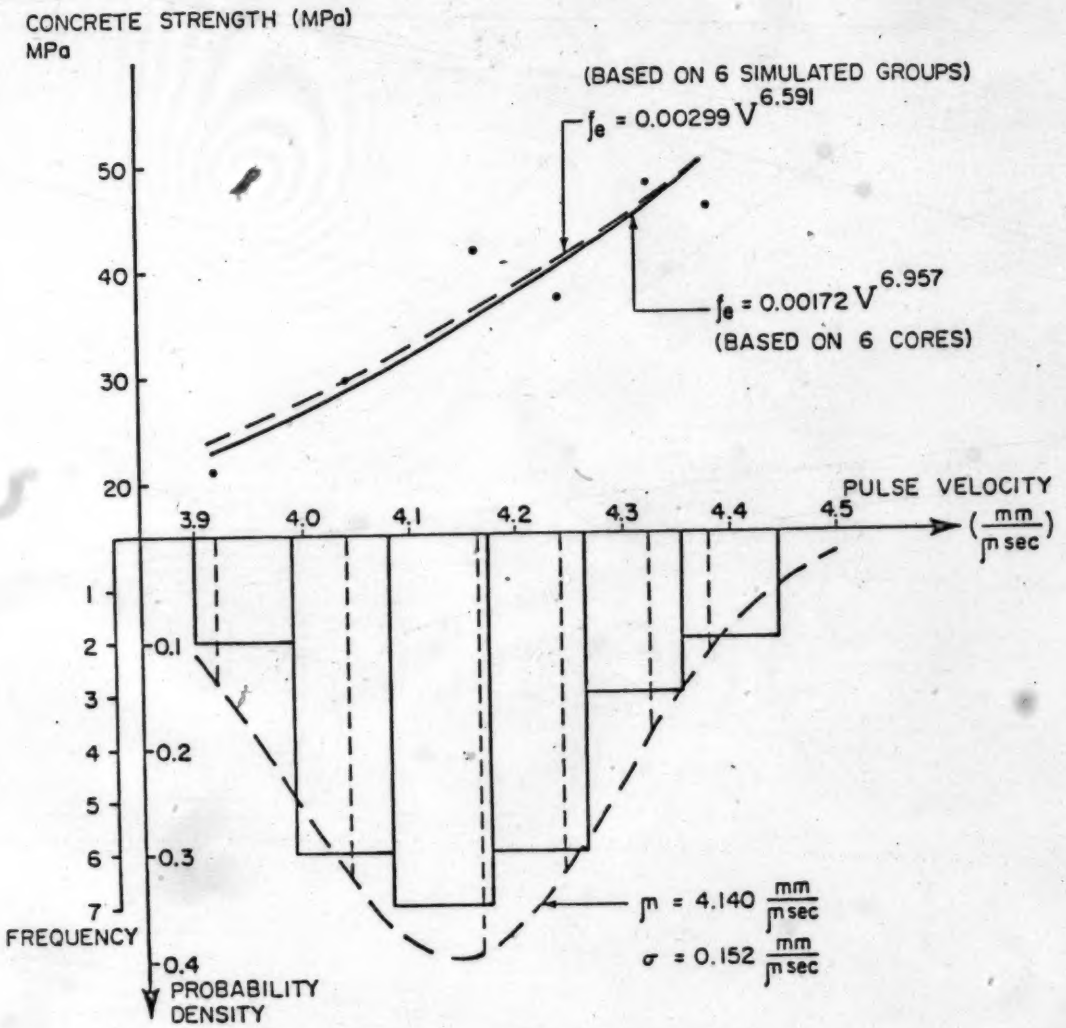


Fig. 6.1 Histogram of 6 Simulated Groups of Cores Based on Probability Density Function of Pulse Velocities of 31 Cores

From a 31 core sample whose histogram is shown in Fig. 6.1.

$\bar{x} = 4.188$ (mm/μsec)

$\hat{\sigma} = 0.131$ (mm/μsec)

$n = 31$

$m = n - 1 = 30$

$t_{\alpha,m} = 2.04$ (95% confidence limit, two tailed test, 30 degrees of freedom)

$$\mu_x = 4.188 \pm 2.04 \frac{0.131}{\sqrt{31}} = 4.188 \pm 0.0048$$

Accepting the lower boundary value of μ_x:

$$\mu_x' = 4.188 - 0.048 = 4.140 \text{ (mm/μsec)}$$

$$\sigma_x = 0.131 \pm 2.04 \frac{0.131}{\sqrt{2 \times 31}} = 0.131 \pm 0.021$$

Accepted $\sigma_x'' = 0.131 + 0.021 = 0.152$ (mm/μsec).

Probability density function of the normal distribution is therefore given by $\mu = 4.140$ (mm/μsec) and $\sigma = 0.152$ (mm/μsec). Table 6.7 shows the ordinates of the probability density function f(x) for pulse velocities in 6 cores and sizes of simulated groups.

Further, regression analysis was performed using mean values of pulse velocities and compressive strength of each simulated group (both provided by the original cores). The resulting regression curve used for calibration was $f_e'' = 0.0030V^{6.591}$ with coefficient of correlation $r = 0.989$. The

histogram based on pulse velocities of simulated groups of cores as well as the resultiing regression curve compared with the original regression curve based on 6 cores are shown in Fig. 6.1. Table 6.8 shows the results of the regression analysis and calculation of the standard error $\hat{\sigma}_t = 3.899$ (MPa).

Table 6.9 gives the estimated values of concrete strength based on pulse velocities of 31 cores and the calibration curve $f_e = 0.0030V^{6.591}$. It also shows that the estimated sample mean of concrete strength is equal to 38.29 MPa with standard deviation $\hat{\sigma}_e = 7.540$ MPa.

In order to calculate the standard error of the population using formula (6.8) the number of degrees of freedom as mentioned earlier is taken as m = (7 + 2) - 1 = 7.

Hence, $t_{95\%,7} = 2.36$ (two tailed test)

Then

$$\sigma_t = \hat{\sigma}_t \pm t_{\alpha,m} \frac{\hat{\sigma}_t}{\sqrt{n^*}} = 3.899 \pm 2.36 \frac{3.899}{\sqrt{8}} = 3.899 \pm 3.253$$

where $n^* = n + 2 = 6 + 2 = 8$

Accepting the upper boundary value of σ_t:

$$\sigma_t'' = 3.899 + 3.253 = 7.152 \text{ (MPa)}$$

From formula (6.8) for 31 samples

Table 6.8 Calibration on 6 Simulated Groups and Calculation of Standard Error

No.	Mean Pulse Velocity of the Group	Mean Compressive Strength of the Group	Group Size λ_j	Results of Regression Analysis		
				f_{je} (1) MPa	$(f'_{jc}-f_{je})^2$	$\lambda_j(f'_{jc}-f_{je})^2$
1	3.917	21.07	2	24.51	11.8336	23.67
2	4.164	41.65	7	36.22	29.4849	206.39
3	4.044	29.79	6	29.87	0.0064	0.04
4	4.252	37.25	6	40.94	13.6161	81.70
5	4.326	47.95	3	46.58	1.8769	5.63
6	4.381	45.76	2	50.63	23.7169	47.43
			Mean Σ 26			364.86

Note: (1) f_{je} $0.0030V^{6.591}$

$$\hat{\sigma}_t = \sqrt{\frac{\Sigma(f'_{ic} - f_{ie})^2}{n-2}} = \sqrt{\frac{364.86}{26-2}} = 3.899$$

Table 6.9 Estimated Values of Concrete Strength Based on Pulse Velocities of 31 Cores and Calibration Curve from 6 Simulated Groups of Cores

No.	Core Number	V $\frac{mm}{\mu sec}$	f'_{ic} MPa	$f_e=0.0299V^{6.5907}$ MPa
1	2	3	4	5
1	AN#32W	4.256	43.42	41.84
2	CN#5W	4.256	32.56	41.84
3	CS#5E	4.204	38.93	38.58
4	BS#3E	3.972	29.42	26.54
5	CS#1E	4.381	45.26	50.63
6	AM#9W	4.326	43.33	46.58
7	AS#5E	4.129	41.82	34.26
8	AS#8E	4.299	37.34	44.70
9	AN#23W	4.274	38.04	43.02
10	BN#31W	4.195	33.49	38.04
11	DN#3E	4.268	35.28	42.62
12	ES#29W	4.035	27.51	29.44
13	EN#8W	4.304	38.44	45.05
14	DS#4E	4.388	44.74	51.17
15	AN#29W	4.286	44.74	43.82
16	CN#1W	3.917	21.07	24.21
17	EN#8E	4.164	41.65	36.22
18	BS#7E	4.148	32.56	35.32
19	DS#31E	4.134	35.16	34.54
20	ES#23W	4.044	29.79	29.87
21	AN#32E	4.293	36.77	44.29
22	CN#5E	4.263	34.34	42.29
23	AM#9E	4.120	36.07	33.78
24	AN#23E	3.993	33.73	27.48
25	BN#31E	4.326	47.95	46.58
26	DN#3W	4.147	37.31	35.26
27	AN#29E	4.337	44.09	47.37
28	CN#1E	3.920	20.33	24.33
29	BN#8W	4.136	35.62	34.65
30	BN#8E	4.084	37.28	31.88
31	BN#4W	4.242	37.25	40.94
	Mean		$\bar{x}_c=36.83$	$\bar{x}_e=38.29$
	Standard Deviation		$\hat{\sigma}_c=6.582$	$\hat{\sigma}_e=7.540$

$$\sigma_t^s = \frac{7.152}{(1 + \frac{2.04}{\sqrt{2 \times 31}})} = 5.680$$

$$\hat{\sigma}_{et} = \sqrt{\hat{\sigma}_e^2 + \hat{\sigma}_t^{s2}} = \sqrt{(7.540)^2 + (5.680)^2} = \sqrt{89.114} = 9.440 \text{ (MPa)}$$

From formula (6.9)

$$\mu_{NDT} = 38.29 \pm 2.04 \frac{9.440}{\sqrt{31}} = 38.29 \pm 3.46$$

Accepting the lower limit value of μ_{NDT}

$$\mu' = 38.29 - 3.46 = 34.83 \text{ (MPa)}$$

Error of the method in comparison with results on 31 cores:

$$\Delta'_{NDT} = \frac{34.42 - 34.83}{34.42} \times 100\% = -1.19\%$$

Sample coefficient of variation v = 9.440/38.29 = 0.247.

Population coefficient of variation from formula (6.6)

$$v = 0.247 \pm 2.04 \frac{0.247}{\sqrt{2 \times 31}} = 0.247 \pm 0.064$$

Accepting the upper limit value of v:

$$v'' = 0.247 + 0.064 = 0.311$$

6.8 Comparison of the Results of Evaluation of the Population Mean of Estimated Concrete Strength of 31 Cores

Results of the estimates of the population mean given in Sections 6.2 through 6.6 i.e. errors of the population means, the population coefficient of variation v" as well as the correction $\pm t_{\alpha,m} \frac{\hat{\sigma}}{\sqrt{n}}$ applied to the sample mean in formula 6.4 in order to estimate the population mean are shown in Table 6.10 for the 4 methods analysed. It appears, that the comparison of the last two parameters provide a better mean of evaluation of the accuracy of each method than the errors of the population means alone.

6.9 Evaluation of Concrete Strength In-Situ

An evaluation was performed using data on pulse velocities and rebound numbers at 69 random locations of the girder stems with a correction factor $\delta = 1.0336$ calculated based on data shown in Table 6.11 and plotted in Figs. 6.2 and 6.3. The resulting data for the 69 locations are presented in Appendix E Table E1. Values of concrete strength were estimated using different calibration curves then the means, standard deviations and coefficients of variation were calculated for each method as shown in Appendix D, Tables D1, D2 and Appendix E, Table E1. Based on these values the population means and coefficients of variation were calculated using formulas (6.4) and (6.6) and compared with those obtained from compression tests on 31 cores from the girder stems. The values of the population

Table 6.10 Errors of the Population Means, Upper Limit Values of the Population Coefficients of Variation, Values of $t_{\alpha,m} \frac{\sigma}{\sqrt{n}}$ (MPa).

	Methods Used to Estimate the Population Mean				
	Compressive Strength of 31 Cores	Calibration on Pulse Velocities of 20 Cores	Calibration on Pulse Velocities and Rebound Numbers of 6 Cores	Calibration on 6 Simulated Groups of Cores	Calibration on Pulse Velocities of 6 Cores
Errors of the Population Means in % in Comparison with the Population Mean Derived From Compressive Strengths of 31 Cores	-	3.40	5.28	-1.19	1.98
v"	0.225	0.264	0.302	0.311	0.332
$\pm t_{\alpha,m} \frac{\hat{\sigma}}{\sqrt{n}}$	2.41	2.76	3.15	3.46	3.61

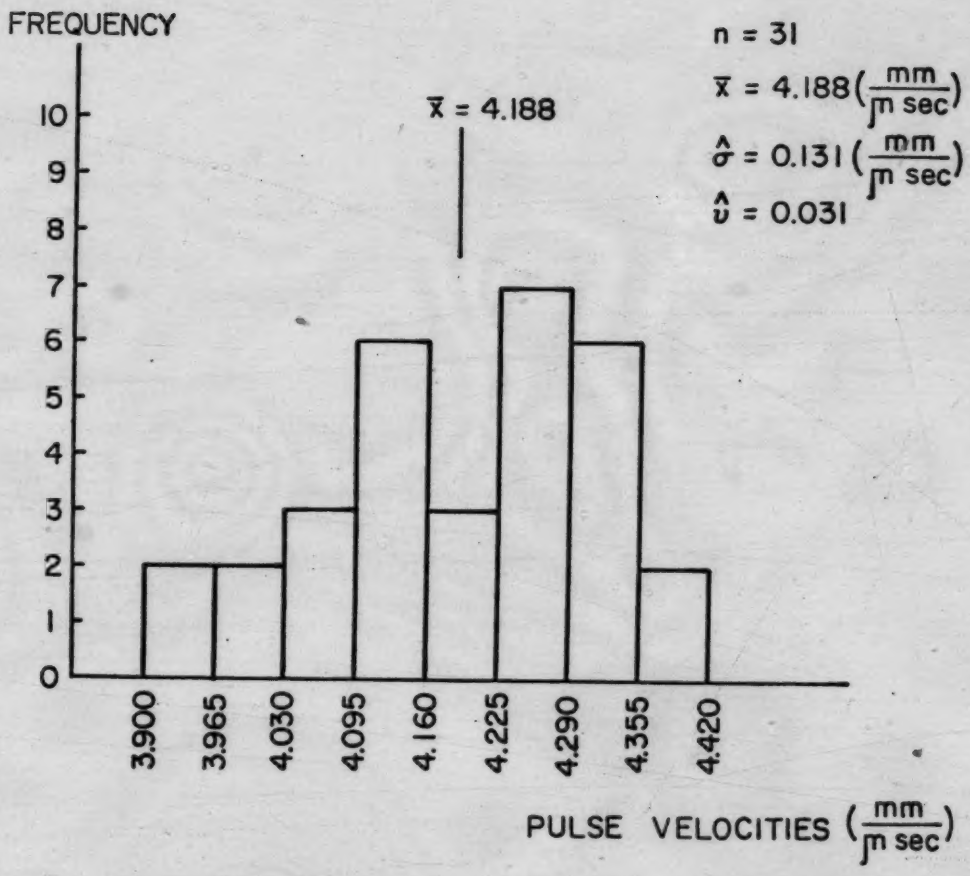


Fig. 6.2 Histogram of Pulse Velocities in 31 Cores

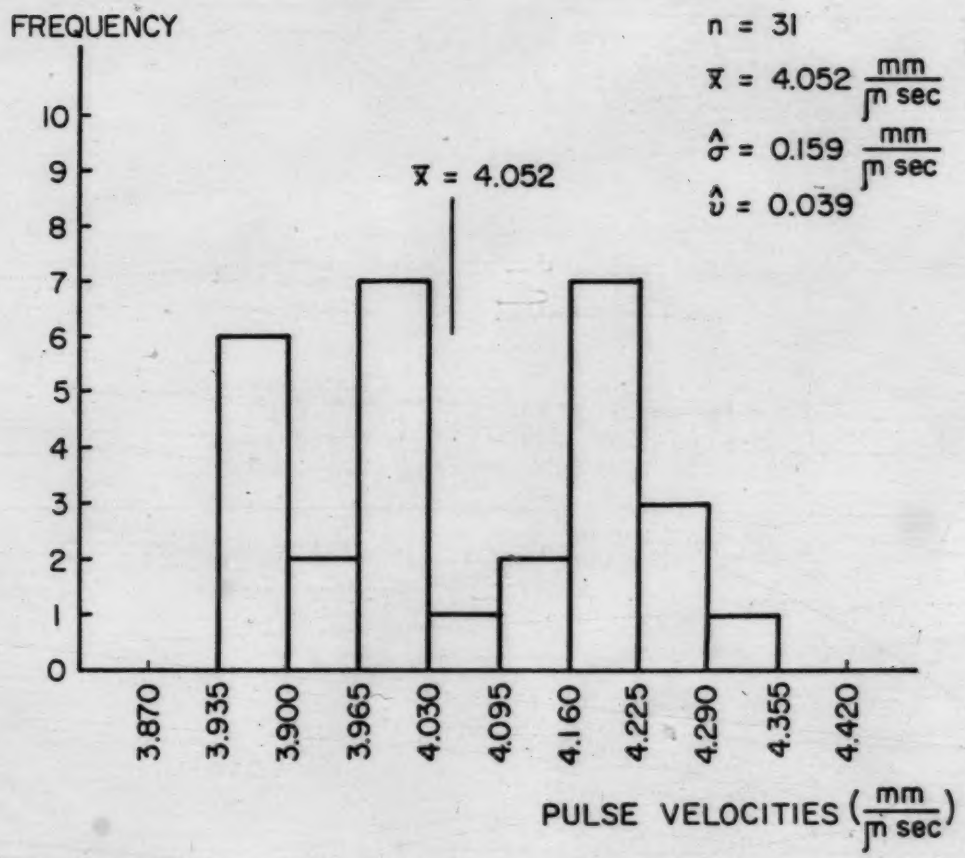


Fig. 6.3 Histogram of Pulse Velocities In-Situ at Location of the Same 31 Cores as in the Figure 6.2.

Table 6.11 Calculation of a Correction Factor Applied to the Pulse Velocities In-Situ

No.	Location	Pulse Velocity In Core $\frac{mm}{\mu sec}$	Pulse Velocity In-Situ $\frac{mm}{\mu sec}$
1	AN#32W	4.256	4.201
2	CN#5W	4.256	4.218
3	CS#5E	4.204	4.060
4	BS#3E	3.972	3.895
5	CS#1E	4.381	4.338
6	AM#9W	4.326	3.841
7	AS#5E	4.129	3.995
8	AS#8E	4.299	3.990
9	AN#23W	4.274	3.871
10	BN#31W	4.195	4.219
11	DN#3E	4.268	3.990
12	ES#29W	4.035	3.849
13	EN#8W	4.304	3.945
14	DS#4E	4.388	4.226
15	AN#29W	4.286	4.271
16	CN#1W	3.917	3.827
17	EN#8E	4.164	3.945
18	BS#7E	4.148	4.133
19	DS#31E	4.134	4.194
20	ES#23W	4.044	4.019
21	AN#32E	4.293	4.201
22	CN#5E	4.263	4.218
23	AM#9E	4.120	3.841
24	AN#23E	3.993	3.871
25	BN#31E	4.326	4.219
26	DN#3W	4.147	3.990
27	AN#29E	4.337	4.271
28	CN#1E	3.920	3.827
29	BN#8W	4.136	4.029
30	BN#8E	4.084	4.029
31	BN#4W	4.242	4.104
Mean		4.188	4.052
Standard Deviation		0.131	0.159
Coefficient of Variation		0.031	0.039

Correction Factor $\delta = \frac{4.188}{4.052} = 1.0336$

means and coefficients of variation are summarized in Table 6.12.

The results from the non-destructive evaluation presented in Table 6.12 are compared with concrete strength obtained from compressive test on 31 cores and 20 cores also given in Table 6.12 as well. The comparison is made through the expression (1.1) given by MacGregor (19)

$$R^*\phi = \bar{R}^*[e^{-\beta\bar{\alpha}V_R}]$$

$\bar{R}^* = \bar{f}'_c$ = mean concrete strength

$V_R = v''$ = coefficient of variation

β = safety index = 3.5

$\bar{\alpha}$ = separation function = 0.75

It can be seen from the data in Table 6.12 that calibration on pulse velocities of 6 cores as well as on pulse velocities of 6 simulated groups of cores are too low, compared with results on 31 cores' compressive strength.

The value of concrete strength obtained through the calibration on rebound numbers of 20 cores would be too high.

The other calibration curves deserve some consideration.

The best result is produced by the calibration curve $f_e = -25.599 + 0.6549R_{min} + 0.1277V^4$, which provided $R^*\phi = 18.2$ MPa vs. $R^*\phi = 19.1$ MPa from compressive tests on 31 cores.

Table 6.12 Summary of the Statistical Evaluation of the In-Situ Concrete Through Different Calibration Curves and Core Tests

No.	Statistical Parameters of Concrete Strength	(1) Calibration on 6 Cores (Pulse Velocity vs. f'_c)	(2) Calibration on 6 Simulated Groups of Cores (Pulse Velocity vs. f'_c)	(3) Calibration on 6 Cores (Pulse Velocity and Minimum Rebound Number vs. f'_c)	(4) Calibration on 20 Cores (Pulse Velocity vs. f'_c)	(5) Calibration on 20 Cores (Pulse Velocity and Minimum Rebound Number vs. f'_c)	(6) Calibration on 20 Cores (Pulse Velocity and Minimum Rebound Number vs. f'_c)	(7) Calibration on 20 Cores (Minimum Rebound Number vs. f'_c)	Compressive Strength of 20 Cores	Compressive Strength of 31 Cores
1	Sample Mean $\bar{x}$	32.2	33.3	34.7	32.1	36.1	36.7	42.2	36.8	36.8
2	Total Sample Standard Deviation $\hat{\sigma}$	11.597	10.787	10.180	8.782	8.519	7.717	7.450	6.648	6.583
3	Total Sample Coefficient of Variation $\hat{v}$	0.360	0.324	0.293	0.274	0.234	0.210	0.177	0.181	0.179
4	Population Mean (8) μ' MPa	29.4	30.7	32.2	30.0	34.0	34.8	40.4	33.7	34.4
5	Coefficient of Variation of Population v'' (9)	0.421	0.379	0.343	0.321	0.274	0.246	0.207	0.266	0.225
6	R^* MPa (10)	9.7	11.4	14.1	12.9	16.6	18.2	23.4	16.8	19.1

Notes: (1) $f_c = 0.00172V^{6.957}$

(2) $f_c = 0.00299V^{6.591}$

(3) $f_c = 0.00203V^{5.237}R^{0.6358}$

(4) $f_c = 0.0200V^{5.227}$

(5) $f_c = 0.0045V^{4.707}R^{0.634}$

(6) $f_c = -25.599 + 0.6549R_{min} + 0.1277V^4$

(7) $f_c = 1.410R^{0.919}$

(8) $\mu' = \bar{x} - t_{\alpha,m}\frac{\hat{\sigma}}{\sqrt{n}}$

(9) $v'' = \hat{v} + t_{\alpha,m}\frac{\hat{v}}{\sqrt{2 \times n}}$

$t_{\alpha,m} = 2.0$ for $\alpha = 95\%$ and $m = n - 1 = 69 - 1 = 68$

$t_{\alpha,m} = 2.09$ for $\alpha = 95\%$ and $m = n - 1 = 20 - 1 = 19$

$t_{\alpha,m} = 2.04$ for $\alpha = 95\%$ and $m = n - 1 = 31 - 1 = 30$

(10) $R^* = \mu' e^{-\beta V_R}$

$V_R = V''$

The difference is $\Delta = \frac{19.1 - 18.2}{19.1} \times 100\% = 4.7\%$.

It is expected that the latter will decrease with an increase of the number of points used for non-destructive test.

Based on compressive test of 20 cores $R^*\phi$ = 16.8 MPa. In this case the difference between the data on 31 cores is $\Delta = \frac{19.1 - 16.8}{19.1} \times 100\% = 12\%$.

7. SUMMARY, CONCLUSIONS, RECOMMENDATIONS

7.1 Summary

A procedure for evaluating concrete strength in-situ was tested on a bridge superstructure. A two-dimensional grid was applied to the vertical surfaces for the identification of test points. Pulse velocity and rebound tests were performed at regularly distributed points of the grid. Thirty-two cores were drilled from the girder stems and 11 cores from the bridge deck. Various dimensions of the superstructure were obtained from measuring on the site and from cores. Statistical parameters of dimensions were evaluated. Correlation of pulse velocities, rebound numbers and densities of concrete samples vs. concrete strength was established. Several calibration curves were developed and compared through a statistical evaluation of results on cores and in-situ. Influence of surface roughness on pulse propagation time was measured and accounted for.

Variability of concrete strength in the structure was evaluated from tests on cores and non-destructive tests in-situ through application of different calibration curves.

7.2 Conclusions

As a result of this study the following may be noted:

1. Accurate measurements of girder configurations can be obtained through a combined use of specially built rigid calipers and common measuring devices (sliding calipers,

tapes).

2. Data on pulse velocity is well correlated with concrete strength in-situ.
3. Correlation of the mean and the maximum rebound numbers in-situ with concrete strength is very poor.
4. Correlation between minimum rebound number and concrete strength is satisfactory.
5. In order to improve the correlation between pulse velocities and concrete strength the loss of the propagation time due to surface roughness should be taken into account.
6. A combined method of testing which involves both the pulse velocity and the rebound number provide a significantly better correlation with concrete strength.
7. The most successful correlation in this study was given by regression formula

$$f'_c = A_o + A_1 R_{min} + A_2 V^4$$

8. Involvement of the concrete density as an additional independent parameter with the above noted combined method does not result in an improved estimate of concrete strength.
9. Correlation of concrete strength in-situ vs. pulse velocities and rebound numbers of a limited number of cores can be improved by introduction of simulated groups of cores based on known statistical distribution

of these parameters in the structure.

10. Application of calibration curves obtained on 20 and possibly fewer cores through a combined method of evaluation provides accurate results of the variability and the mean strength of the concrete in-situ.
11. Evaluation of the capacity of the tested structure based on specified concrete strength and dimensions would lead to a significant underestimation.
12. Selection of points of coring based on a known distribution of pulse velocities in-situ improves a chance for a successful calibration with a limited number of cores.
13. Application of calibration curves to the results of non-destructive test provides the information on 3-dimensional variability of concrete strength in the structure.

7.3 Recommendations

The following procedure is recommended for an evaluation of the capacity of an existing bridge superstructure.

1. Application of an identification grid (approximate size of cells 0.4 m x 0.4 m).
2. Pulse velocity testing at regularly distributed points of the grid (approximately 0.4 m apart).
3. Rebound number tests within grid cells.
4. Obtaining of the dimensions of the structure.

5. Selection of core locations based on distribution of pulse velocities and rebound numbers so that a satisfactory range of these parameters will be represented in cores.
6. Coring at selected points.
7. Obtaining of rebound numbers around core holes.
8. Pulse velocity testing of cores with natural and smooth cut surfaces.
9. Compressive test of cores.
10. Development of a calibration formula through a regression analysis between non-destructive tests and concrete strength.
11. Application of the calibration formula to the non-destructive test results in-situ.
12. Statistical evaluation of non-destructive testing of concrete strength.
13. Statistical evaluation of the dimensions of the structure.
14. Evaluation of the capacity of the structure using the probabilistic approach with statistical parameters of dimensions and concrete strength obtained.

Future research into nondestructive evaluation of concrete strength may be conducted in the following areas:

1. Establishment of typical calibration curves applicable to different bridge structures through similar studies.
2. Evaluation of an optimum number of cores needed for a successful calibration between non-destructive tests and

concrete strength through a creation of simulated populations on core samples based on results of this and similar studies.

3. Evaluation of the influence of the variability of surface roughness on the correlation between the actual and the estimated concrete strength based on simulated populations of concrete samples with different thicknesses and strengths of concrete.
4. Evaluation of variations in pulse velocities due to variations in stress fields in structures.

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APPENDIX

APPENDIX A
RESULTS OF DATA COLLECTION

Table A1. Pulse Velocities in Cells of Zone AN $V = \frac{\ell}{\tau}$

Point Number	Time Reading t μsec	d mm	ℓ = 529-d mm	τ = t-2.4 μsec	V $\frac{mm}{\mu sec}$
1	2	3	4	5	6
1	112.0	112.0	417.0	109.6	3.805
2	108.9	111.0	418.0	106.5	3.925
3	105.3	110.8	418.2	102.9	4.064
4	104.3	110.4	418.6	101.9	4.108
5	104.3	106.1	422.9	101.9	4.150
6	107.5	100.6	428.4	105.1	4.076
7	105.3	101.8	427.2	102.9	4.152
8	103.6	104.6	424.4	101.2	4.194
9	107.3	102.3	426.7	104.9	4.068
10	106.4	100.0	429.0	104.0	4.125
11	115.3	98.0	431.0	112.9	3.828
12	119.8	101.0	428.0	117.4	3.646
13	114.7	95.2	433.8	112.3	3.863
14	111.8	94.2	434.8	109.4	3.974
15	114.8	89.4	439.6	112.4	3.911
16	122.2	88.5	439.5	119.8	3.669
17	127.4	83.5	445.5	125.0	3.564
18	125.2	85.1	443.9	122.8	3.615
19	118.4	86.6	442.4	116.0	3.814
20	117.3	90.8	438.2	114.9	3.814
21	115.6	90.4	438.6	113.2	3.875
22	115.5	92.2	436.8	113.1	3.862
23	116.2	88.5	440.5	113.8	3.871
24	112.6	93.0	436.0	110.3	3.952
25	108.0	53.2	435.8	105.6	4.127
26	109.7	92.2	438.8	107.3	4.089
27	108.3	95.5	433.5	105.9	4.093
28	107.6	97.0	432.0	105.2	4.106
29	103.7	97.6	431.4	101.3	4.271
30	110.7	93.3	435.7	108.3	4.023
31	105.7	100.5	428.5	103.3	4.148
32	103.9	102.6	426.4	101.5	4.201
33	111.4	93.0	436.0	109.0	4.000
34	108.8	92.8	436.2	106.4	4.100
35	112.2	92.0	437.0	109.8	4.980
36	111.0	91.3	437.7	108.6	4.030
37	114.6	93.0	436.0	112.2	3.886
38	129.6	94.5	434.5	127.2	3.416

Table A2. Pulse Velocities in Cells of Zone AM

Point Number	Time Reading t μsec	d mm	ℓ = 524.6-d mm	τ = t-2.4 μsec	V $\frac{mm}{\mu sec}$
1	2	3	4	5	6
1	117.6	85.1	443.9	115.2	3.853
2	115.8	83.4	445.6	113.4	3.929
3	112.7	90.5	438.5	110.3	3.976
4	112.2	93.5	435.5	109.8	3.966
5	113.7	94.5	434.5	111.3	3.961
6	113.3	94.0	435.0	110.9	3.922
7	106.3	97.4	431.6	103.9	4.154
8	114.6	96.0	433.0	112.2	3.859
9	115.0	96.5	432.5	112.6	3.841
10	111.2	97.5	431.5	108.8	3.966
11	114.2	95.5	433.5	111.8	3.877
12	109.7	96.3	432.7	107.3	4.033
13	112.3	94.5	434.5	109.9	3.954
14	106.4	96.0	433.0	104.0	4.163
15	111.0	97.0	432.0	108.6	3.978
16	109.7	101.5	429.5	107.3	4.003

Table A3. Pulse Velocities in Cells of Zone AS

Point Number	Time Reading t μsec	d mm	ℓ = 524.6-d mm	τ = t-2.4 μsec	V $\frac{\text{mm}}{\mu\text{sec}}$
1	2	3	4	5	6
1	113.7	80.0	444.6	111.3	3.995
2	114.3	76.8	447.6	111.9	4.000
3	113.0	77.6	447.0	110.6	4.042
4	110.3	81.4	443.2	107.9	4.108
5	113.3	81.6	443.0	110.9	3.995
6	107.3	82.5	442.1	104.9	4.214
7	117.2	84.7	439.9	114.8	3.832
8	112.8	84.5	440.1	110.3	3.990
9	110.8	82.3	442.3	108.4	4.080
10	110.2	80.9	443.7	107.8	4.116
11	110.6	84.7	439.9	108.2	4.066
12	106.8	91.3	433.3	104.4	4.150
13	112.3	90.7	433.9	109.9	3.948
14	111.3	90.3	434.3	108.9	3.988
15	104.3	92.3	432.3	101.9	4.242
16	104.4	89.3	435.3	102.0	4.268
17	124.8	90.0	434.6	122.4	3.551
18	120.4	88.7	435.9	118.0	3.694
19	125.3	84.9	439.7	122.9	3.578
20	114.2	87.0	437.6	111.8	3.914
21	111.2	88.2	436.4	107.8	4.048
22	111.8	84.0	440.6	109.4	4.027
23	116.5	80.2	444.4	114.1	3.895
24	110.7	80.2	444.4	108.3	4.103
25	110.3	82.2	442.4	107.9	4.100
26	116.4	80.0	444.6	114.0	3.900
27	113.6	78.1	446.5	111.2	4.015
28	111.6	79.0	445.6	109.2	4.081
29	117.6	75.7	448.9	115.2	3.897
30	113.2	74.1	450.5	110.8	4.066
31	119.4	72.6	452.0	117.0	3.863
32	113.2	76.6	448.0	110.8	4.043
33	116.3	83.3	441.3	113.9	3.874
34	120.0	79.5	445.1	117.6	3.785
35	rough	76.3	448.3	rough	rough
36	rough	78.0	446.6	rough	rough
37	rough	78.3	446.3	rough	rough
38	rough	75.8	448.8	rough	rough

Table A4. Pulse Velocities in Cells of Zone BN

Point Number	Time Reading t μsec	d mm	ℓ = 534.6-d mm	τ = t-2.5 μsec	V mm/μsec
1	2	3	4	5	6
1	108.4	85.0	449.6	106.0	4.242
2	111.7	90.9	443.7	109.3	4.059
3	117.4	85.0	449.6	115.0	3.910
4	109.8	83.8	440.8	107.4	4.104
5	117.1	90.6	444.0	114.7	3.871
6	112.6	102.0	432.6	110.2	3.926
7	114.6	97.1	437.5	112.2	3.899
8	110.2	100.3	434.3	107.8	4.029
9	115.4	100.5	434.1	113.0	3.842
10	109.6	103.3	431.3	107.2	4.023
11	111.2	97.2	437.4	108.8	4.020
12	111.3	98.7	435.9	108.9	4.003
13	119.8	92.0	442.6	117.4	3.770
14	107.0	98.3	436.3	104.6	4.171
15	112.3	92.8	441.8	109.9	4.020
16	112.0	96.6	436.0	109.6	3.978
17	117.6	98.4	436.2	115.2	3.786
18	112.6	95.3	439.3	110.2	3.986
19	107.6	96.5	438.1	105.2	4.164
20	108.3	98.5	436.1	105.9	4.118
21	114.7	97.1	437.5	112.3	3.896
22	111.8	103.1	431.5	109.4	3.944
23	112.8	100.7	433.9	110.4	3.930
24	110.6	97.8	436.8	108.2	4.037
25	110.5	100.8	433.8	108.1	4.013
26	111.6	101.4	433.2	109.2	3.967
27	109.6	101.5	433.1	107.2	4.040
28	111.8	97.1	437.5	109.4	3.999
29	108.6	102.1	432.5	106.2	4.072
30	113 ~~.2~~	90.4	444.2	110.8	4.009
31	107.1	92.9	441.7	104.7	4.219
32	111.0	97.0	437.6	108.6	4.029
33	108.0	102.0	432.6	105.6	4.097
34	110.5	108.2	426.4	108.1	3.944
35	106.2	108.6	426.0	103.8	4.104
36	106.3	109.4	425.2	103.9	4.092
37	106.7	107.3	427.3	104.3	4.097
38	108.4	107.0	427.0	106.0	4.028

Table A5. Pulse Velocities in Cells of Zone BM

Point Number	Time Reading t μsec	d mm	ℓ = 534.6-d mm	τ = t-2.4 μsec	V $\frac{mm}{\mu sec}$
1	2	3	4	5	6
1	114.6	94.7	439.9	112.2	3.921
2	113.8	100.7	433.9	111.4	3.895
3	109.4	97.5	437.1	107.0	4.081
4	120.5	98.2	436.4	118.1	3.695
5	112.3	102.8	431.8	109.9	3.929
6	113.0	109.6	425.0	110.6	3.843
7	118.7	108.3	426.3	116.3	3.666
8	106.7	92.6	442.0	114.3	3.867
9	111.7	93.9	440.7	109.3	4.032
10	122.6	99.7	434.9	120.2	3.618
11	116.3	95.6	439.0	113.9	3.854
12	111.7	97.8	436.8	109.3	3.996
13	105.6	96.4	438.2	103.2	4.246
14	110.4	96.5	438.1	108.0	4.056
15	113.3	94.9	440.1	110.9	3.968
16	110.7	98.2	436.4	108.3	4.030

Table A6. Pulse Velocities in Cells of Zone BS

Point Number	Time Reading t μsec	d mm	ℓ = 534.6-d mm	τ = t-2.4 μsec	V $\frac{mm}{\mu sec}$
1	2	3	4	5	6
1	113.4	103.2	431.4	111.0	3.886
2	109.2	97.5	437.1	106.8	4.093
3	115.8	92.7	441.7	113.4	3.895
4	114.5	97.8	436.8	112.1	3.896
5	110.8	98.4	436.2	108.4	4.024
6	114.7	91.7	442.9	112.3	3.944
7	109.1	93.6	441.0	106.7	4.133
8	114.8	91.0	443.6	112.4	3.947
9	116.6	97.2	437.4	114.2	3.830
10	106.6	92.8	441.8	104.2	4.240
11	110.7	94.8	439.8	108.3	4.061
12	114.8	91.6	443.0	112.4	3.941
13	107.8	92.1	442.5	105.4	4.198
14	110.7	99.5	435.1	108.3	4.018
15	107.0	96.0	438.6	104.6	4.193
16	109.7	98.5	436.1	107.3	4.064
17	128.6	100.8	433.8	126.2	3.437
18	117.7	96.1	438.5	115.4	3.800
19	113.7	100.8	433.8	111.4	3.894
20	114.3	97.0	437.6	111.9	3.910
21	115.8	92.0	442.6	113.4	3.903
22	115.7	97.0	437.6	113.3	3.862
23	105.4	101.8	432.8	113.0	3.830
24	116.2	106.6	428.0	113.8	3.761
25	111.0	97.3	437.3	108.6	4.027
26	112.6	99.9	434.7	110.2	3.945
27	117.4	100.1	434.5	115.0	3.778
28	113.4	102.3	432.3	111.0	3.895
29	113.7	103.8	430.8	111.3	3.871
30	117.4	96.8	437.8	115.0	3.807
31	115.2	98.0	436.6	112.8	3.871
32	108.4	102.0	432.6	106.0	4.081
33	114.6	96.4	438.2	112.2	3.906
34	116.3	90.3	444.3	113.9	3.901
35	117.6	96.8	437.8	115.2	3.800
36	115.6	104.6	430.0	113.2	3.799
37	rough	surface			
38	rough	surface			

Table A7. Pulse Velocities in Cells of Zone CN

Point Number	Time Reading t μsec	d mm	ℓ = 524.6-d mm	τ = t-2.4 μsec	V $\frac{mm}{\mu sec}$
1	2	3	4	5	6
1	115.3	90.6	434.0	113.4	3.827
2	114.3	95.1	429.5	111.9	3.838
3	108.3	92.3	432.3	105.9	4.082
4	111.4	96.2	428.4	109.0	3.930
5	103.3	100.3	424.3	100.6	4.218
6	116.8	95.7	428.9	114.4	3.749
7	102.2	100.4	424.2	100.8	4.208
8	114.7	99.7	424.9	112.3	3.784
9	104.2	100.0	424.6	101.8	4.171
10	104.3	103.0	421.6	101.9	4.137
11	104.7	102.7	421.9	102.3	4.124
12	106.4	98.1	426.5	104.0	4.101
13	106.4	94.3	430.3	104.0	4.138
14	114.0	93.1	431.5	111.6	3.866
15	110.4	95.4	429.2	108.0	3.974
16	106.3	97.3	427.3	103.9	4.113
17	118.8	95.2	429.4	116.4	3.689
18	111.3	94.8	429.8	108.9	3.947
19	115.0	94.6	430.0	112.6	3.819
20	117.6	92.5	432.1	115.2	3.751
21	106.5	98.1	426.5	104.1	4.097
22	105.4	100.7	423.9	103.0	4.116
23	103.2	101.3	423.3	100.8	4.199
24	105.4	103.8	420.8	102.9	4.089
25	104.3	100.7	423.9	101.9	4.160
26	104.4	97.7	426.9	102.0	4.185
27	104.4	95.4	429.2	102.0	4.208
28	107.2	100.5	424.1	104.8	4.047
29	108.3	95.5	429.1	105.9	4.052
30	106.3	93.6	431.0	103.9	4.148
31	109.5	88.6	436.0	107.1	4.071
32	119.3	88.2	436.4	116.9	3.733
33	111.3	91.6	433.0	108.9	3.976
34	106.7	92.3	432.3	104.3	4.145
35	107.1	98.2	426.4	104.7	4.073
36	108.7	98.6	426.0	106.3	4.008
37	111.6	96.8	427.8	109.2	3.918
38	119.3	97.0	427.6	116.9	3.658

Table A8. Pulse Velocities in Cells of Zone CM

Point Number	Time Reading t μsec	d mm	ℓ = 524.6-d mm	τ = t-2.4 μsec	V $\frac{\text{mm}}{\mu\text{sec}}$
1	2	3	4	5	6
1	108.7	96.9	427.7	106.3	4.024
2	111.7	97.6	427.0	109.3	3.907
3	103.2	92.8	431.8	100.8	4.284
4	116.3	91.2	433.4	113.9	3.805
5	110.7	88.3	436.3	108.3	4.029
6	125.3	89.1	435.5	122.9	3.544
7	116.8	89.0	435.6	114.4	3.809
8	115.6	93.3	431.3	113.2	3.810
9	107.3	94.6	430.3	104.9	4.102
10	114.3	97.6	427.0	111.9	3.816
11	107.8	96.6	428.0	105.4	4.061
12	113.3	93.9	430.7	110.9	3.884
13	107.8	89.0	435.6	105.4	4.133
14	112.6	84.0	440.6	110.2	3.998
15	110.7	88.0	436.6	108.3	4.031
16	104.3	91.2	433.4	101.9	4.253

Table A9. Pulse Velocities in Cells of Zone CS

Point Number	Time Reading t μsec	d mm	ℓ = 524.6-d mm	τ = t-2.4 μsec	V mm/μsec
1	2	3	4	5	6
1	107.4	69.1	455.5	105.0	4.338
2	113.2	63.0	461.6	110.8	4.166
3	120.6	60.5	464.1	118.2	3.926
4	108.7	61.8	462.8	106.3	4.354
5	115.8	64.2	460.4	113.4	4.060
6	108.6	63.2	461.4	106.2	4.345
7	108.0	64.2	460.4	105.6	4.360
8	113.2	77.0	447.6	110.8	4.117
9	117.1	77.0	447.6	114.7	3.902
10	111.5	79.4	445.2	109.1	4.081
11	116.3	82.5	442.1	113.9	3.881
12	109.6	80.5	444.1	107.2	4.143
13	107.6	84.4	440.2	105.2	4.184
14	104.7	85.4	439.2	102.3	4.299
15	106.4	87.1	437.5	104.0	4.207
16	108.8	85.9	438.7	106.4	4.123
17	119.3	90.5	434.1	116.9	3.713
18	111.6	87.7	436.9	109.2	4.001
19	113.8	90.0	434.6	111.4	3.901
20	114.2	87.8	436.8	111.8	3.907
21	110.4	86.2	438.4	108.0	4.059
22	110.3	83.8	440.8	107.9	4.085
23	114.2	81.8	442.8	111.8	3.961
24	107.8	76.8	447.8	105.4	4.249
25	116.7	73.3	451.3	114.3	3.948
26	112.0	65.4	459.2	109.6	4.190
27	117.2	62.3	462.3	114.8	4.027
28	117.3	67.2	457.4	114.9	3.981
29	111.7	62.8	461.8	109.3	4.225
30	112.8	60.7	463.9	110.4	4.202
31	113.5	65.5	459.1	111.1	4.132
32	109.6	74.2	450.4	107.2	4.201
33	116.1	72.5	447.1	113/8	3.932
34	118.3	71.0	453.6	115.9	3.914
35	117.0	69.6	455.0	114.6	3.970
36	117.8	69.6	455.0	115.4	3.943
37	125.8	70.3	454.3	123.4	3.682
38	122.2	70.4	454.2	119.8	3.791

Table A10. Pulse Velocities in Cells of Zone DN

Point Number	Time Reading t μsec	d mm	ℓ = 524.6-d mm	τ = t-2.4 μsec	V $\frac{mm}{\mu sec}$
1	2	3	4	5	6
1	118.4	72.9	451.7	116.0	3.894
2	116.6	67.8	456.8	114.2	4.000
3	116.8	68.1	456.5	114.4	3.990
4	129.8	62.4	462.2	127.4	3.628
5	118.6	67.4	457.2	116.2	3.935
6	120.7	63.3	461.3	118.3	3.899
7	122.7	67.6	457.0	120.3	3.799
8	121.7	65.4	459.2	119.3	3.849
9	115.3	72.4	452.2	112.9	4.005
10	116.2	76.0	448.6	113.8	3.942
11	116.6	81.6	443.0	114.2	3.879
12	116.3	79.6	445.0	113.9	3.907
13	120.7	82.8	441.8	118.3	3.734
14	118.7	89.4	435.2	116.3	3.742
15	118.4	87.1	437.5	116.0	3.980
16	111.7	89.6	435.0	109.3	3.980
17	115.7	108.6	416.0	113.3	3.672
18	115.6	101.8	422.8	113.2	3.735
19	118.5	93.3	431.3	116.1	3.715
20	116.6	87.2	437.4	114.2	3.830
21	120.6	87.6	437.0	118.2	3.697
22	118.8	85.2	439.4	116.4	3.775
23	118.3	79.5	445.1	115.9	3.840
24	114.0	77.2	447.4	111.6	4.009
25	110.8	75.9	448.7	108.4	4.139
26	116.2	73.4	451.2	113.8	3.965
27	113.8	68.9	455.7	111.4	4.091
28	113.4	79.0	445.6	111.0	4.014
29	115.9	70.8	454.8	113.5	4.007
30	110.8	77.4	447.2	108.4	4.125
31	117.4	74.0	450.6	115.0	3.918
32	109.3	79.7	444.9	106.9	4.162
33	110.2	83.1	441.5	107.8	4.096
34	112.3	82.8	441.8	109.9	4.020
35	109.2	83.6	441.0	106.8	4.129
36	113.0	81.2	443.4	110.6	4.009
37	116.3	82.6	442.0	113.9	3.881
38	114.6	82.1	442.5	112.2	3.944

Table A11. Pulse Velocities in Cells of Zone DM

Point Number	Time Reading t μsec	d mm	ℓ = 524.6-d mm	τ = t-2.4 μsec	V $\frac{mm}{\mu sec}$
1	2	3	4	5	6
1	108.5	92.8	431.8	106.1	4.070
2	116.2	92.7	431.9	113.8	3.795
3	110.3	89.2	435.4	107.9	4.035
4	112.6	90.2	434.4	110.2	3.942
5	111.7	83.2	441.4	109.3	4.038
6	120.3	91.3	433.3	117.9	3.675
7	110.8	89.4	435.2	108.4	4.015
8	115.4	89.5	435.1	113.0	3.850
9	109.2	84.0	440.6	106.8	4.125
10	134.7	87.8	436.8	132.3	3.302
11	110.5	84.9	439.7	108.1	4.068
12	118.3	86.1	438.5	115.9	3.783
13	109.4	87.9	436.7	107.0	4.081
14	115.6	87.2	437.4	113.2	3.864
15	116.7	80.3	444.3	114.3	3.887
16	122.4	80.4	444.2	120.0	3.702

Table A12. Pulse Velocities in Cells of Zone DS

Point Number	Time Reading t μsec	d mm	ℓ = 524.6-d mm	τ = t-2.4 μsec	V $\frac{\text{mm}}{\mu\text{sec}}$
1	2	3	4	5	6
1	112.3	63.8	460.8	109.9	4.193
2	111.1	71.1	453.5	108.7	4.172
3	116.0	61.6	463.0	113.6	4.076
4	110.8	66.5	458.1	108.4	4.226
5	114.0	66.9	457.7	111.6	4.101
6	116.0	70.7	453.9	113.6	3.996
7	114.6	69.4	455.2	112.2	4.057
8	122.6	67.2	457.4	120.2	3.806
9	114.7	66.0	458.6	112.3	4.084
10	119.0	68.6	456.0	116.6	3.911
11	115.3	66.6	458.0	112.9	4.057
12	117.3	68.9	455.7	114.9	3.966
13	112.5	76.2	448.4	110.1	4.073
14	118.4	75.5	449.1	116.0	3.872
15	113.3	80.3	444.3	110.9	4.006
16	112.6	83.0	441.6	110.2	4.007
17	117.0	86.0	438.6	114.6	3.827
18	116.6	79.0	445.6	114.2	3.902
19	117.4	74.2	450.4	115.0	3.917
20	118.7	76.6	448.0	116.3	3.852
21	113.1	76.9	447.7	110.7	4.044
22	115.4	77.7	446.9	113.0	3.955
23	117.0	69.5	455.1	114.6	3.971
24	116.0	73.6	451.0	113.6	3.970
25	115.7	74.3	450.3	113.3	3.974
26	113.0	74.6	450.0	110.6	4.069
27	113.6	73.8	450.8	111.2	4.054
28	115.2	74.8	449.8	112.8	3.988
29	111.6	81.8	442.8	109.2	4.055
30	107.0	75.8	448.8	104.6	4.291
31	108.6	79.2	445.4	106.2	4.194
32	111.3	77.1	447.5	108.9	4.109
33	103.7	92.2	432.4	101.3	4.269
34	106.7	77.1	447.5	104.3	4.291
35	112.0	92.8	431.8	109.6	3.940
36	112.4	90.0	434.6	110.0	3.951
37	120.7	82.2	442.4	118.3	3.740
38	118.4	82.3	442.3	116.0	3.813

Table A13. Pulse Velocities in Cells of Zone EN

Point Number	Time Reading t μsec	d mm	ℓ = 525.6-d mm	τ = t-2.4 μsec	V $\frac{\text{mm}}{\mu\text{sec}}$
1	2	3	4	5	6
1	115.2	77.8	447.8	112.8	3.970
2	118.6	81.3	444.3	116.2	3.824
3	114.3	80.6	445.0	111.9	3.977
4	116.5	76.0	449.6	114.1	3.940
5	114.6	73.9	451.7	112.2	4.026
6	114.6	75.6	450.0	112.2	4.011
7	113.5	76.5	449.1	111.1	4.042
8	115.2	80.6	445.0	112.8	3.945
9	114.3	87.5	438.2	111.9	3.916
10	111.0	90.5	435.1	108.6	4.006
11	111.6	89.0	436.6	109.2	3.998
12	113.0	93.5	432.1	110.6	3.907
13	107.4	97.4	428.2	105.0	4.078
14	110.8	95.6	430.0	108.4	3.967
15	119.3	86.7	438.9	116.9	3.754
16	120.6	93.1	432.5	118.2	3.659
17	126.0	96.8	428.8	123.6	3.469
18	126.4	98.5	427.1	124.0	3.444
19	115.7	99.0	426.6	113.3	3.765
20	117.6	99.6	426.0	115.2	3.698
21	113.0	97.3	428.3	110.6	3.873
22	113.7	92.8	432.8	111.3	3.889
23	110.1	91.4	434.2	107.7	4.032
24	110.7	89.0	436.6	108.3	4.031
25	113.6	85.4	440.2	111.2	3.959
26	114.4	80.8	444.8	112.0	3.971
27	113.7	73.9	451.7	111.3	4.058
28	117.4	73.6	452.0	115.0	3.930
29	113.6	73.9	451.7	111.2	4.062
30	112.6	73.8	451.8	110.2	4.100
31	116.3	73.8	451.8	113.9	3.967
32	118.8	72.8	452.8	116.4	3.890
33	114.3	70.7	448.9	111.9	4.012
34	117.2	75.5	450.1	114.8	3.921
35	117.6	77.5	448.1	115.2	3.890
36	117.7	77.9	447.7	115.3	3.883
37	115.1	75.6	450.0	112.7	3.993
38	112.3	77.4	448.2	109.9	4.078

Table A14. Pulse Velocities in Cells of Zone EM

Point Number	Time Reading t μsec	d mm	ℓ = 525.6-d mm	τ = t-2.4 μsec	V $\frac{\text{mm}}{\mu\text{sec}}$
1	2	3	4	5	6
1	117.2	93.0	432.6	114.8	3.768
2	112.2	93.0	432.6	109.8	3.940
3	113.3	96.3	429.3	110.9	3.871
4	116.7	94.9	430.7	114.3	3.768
5	117.6	92.8	432.8	115.2	3.757
6	115.6	91.2	434.4	113.2	3.837
7	109.4	89.9	435.7	107.0	4.072
8	111.3	87.2	438.4	108.9	4.026
9	118.3	86.0	439.6	115.9	3.793
10	114.3	87.7	437.9	111.9	3.913
11	117.0	88.9	436.7	114.6	3.811
12	114.3	94.2	431.4	111.9	3.855
13	114.3	92.8	432.8	111.9	3.868
14	119.2	95.5	430.1	116.8	3.682
15	110.0	94.0	431.6	107.6	4.011
16	108.3	97.4	428.2	105.9	4.043

Table A15. Pulse Velocities in Cells of Zone ES

Point Number	Time Reading t μsec	d mm	ℓ = 524.6-d mm	τ = t-2.4 μsec	V $\frac{\text{mm}}{\mu\text{sec}}$
1	2	3	4	5	6
1	114.2	88.0	436.6	111.8	3.905
2	114.4	86.3	438.3	112.0	3.913
3	118.4	84.4	440.2	116.0	3.795
4	116.4	84.0	440.6	114.0	3.865
5	115.6	79.7	444.9	113.2	3.930
6	114.3	83.5	441.1	111.9	3.942
7	111.3	87.3	437.3	108.9	4.016
8	109.5	90.1	434.5	107.1	4.057
9	111.4	97.8	426.8	109.0	3.916
10	110.6	90.0	434.6	108.2	4.017
11	109.2	92.8	431.8	106.8	4.043
12	108.1	92.2	432.4	105.7	4.091
13	109.4	90.2	434.4	107.0	4.060
14	108.3	92.8	431.8	105.9	4.077
15	96.8	95.8	428.8	94.4	4.542*
16	94.6	95.1	429.5	92.2	4.658*
17	111.6	90.4	434.2	109.2	3.976
18	99.7	93.0	431.6	97.3	4.436*
19	107.5	89.1	435.5	105.1	4.144
20	110.4	88.8	435.8	108.0	4.035
21	113.2	89.4	435.2	110.8	3.928
22	113.0	90.5	434.1	110.6	3.925
23	110.5	90.2	434.4	108.1	4.019
24	108.3	94.8	429.8	105.9	4.059
25	109.6	91.0	433.6	107.2	4.045
26	110.4	86.7	437.9	108.0	4.055
27	113.0	87.0	437.6	110.6	3.957
28	116.3	83.4	441.2	113.9	3.874
29	117.3	82.4	442.2	114.9	3.849
30	111.1	84.5	440.1	108.7	4.049
31	116.3	74.4	450.2	113.9	3.953
32	110.0	79.6	445.0	107.6	4.136
33	113.6	77.5	447.1	111.2	4.021
34	109.7	77.3	447.3	107.3	4.167
35	111.5	78.6	446.0	109.1	4.088
36	115.6	83.6	441.0	113.2	3.896
37	113.5	83.3	441.3	111.1	3.972
38	114.7	84.4	440.2	112.3	3.920

* Concentration of Reinforcement

Table A16. Rebound Numbers in Cells of Zone AN

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	45	51	38	30	54	56	38	51	45	46.3	38
2	41	54	57	45	52	40	49	49	54	49.0	40
3	47	40	49	50	45	36	40	48	50	45.0	36
4	48	55	55	56	49	42	50	42	53	50.0	42
5	57	54	52	46	55	46	45	44	55	50.4	44
6	49	49	50	55	53	54	50	47	50	50.8	47
7	52	50	52	51	50	45	52	50	41	49.2	41
8	54	52	54	49	46	54	50	48	54	51.2	46
9	50	54	40	45	56	47	51	53	44	48.9	40
10	41	46	42	56	57	59	53	43	52	49.9	41
11	50	48	48	53	53	49	44	48	52	49.4	44
12	54	46	49	56	58	44	53	41	42	49.2	41
13	59	56	50	49	43	45	40	50	40	48.0	40
14	50	52	50	47	49	48	46	45	48	48.1	44
15	46	44	45	50	50	49	48	43	51	47.3	43
16	50	50	43	42	55	52	56	53	44	49.4	42
17	49	51	53	53	56	41	51	45	42	49.0	41
18	50	57	46	48	56	59	54	54	53	52.7	44
19	53	46	56	47	52	47	55	48	52	50.7	46
20	48	47	44	56	59	42	53	56	54	49.9	42
21	44	53	42	41	46	44	56	58	55	48.8	41
22	39	42	40	48	41	49	45	57	58	46.6	39
23	46	42	39	51	47	45	53	53	44	46.7	39
24	51	53	44	45	44	47	54	60	52	50.0	44
25	43	46	43	49	52	52	46	47	47	47.2	43
26	44	52	48	49	54	51	49	42	43	48.0	41
27	40	46	44	54	45	54	45	44	56	47.6	40
28	52	55	47	55	53	55	37	43	52	51.0	43
29	44	48	47	53	45	41	50	50	46	47.1	41
30	50	43	50	47	53	47	52	53	50	49.4	43
31	55	52	44	50	49	50	51	53	56	51.1	44
32	57	52	47	57	42	49	46	42	57	49.9	42
33	57	54	51	43	42	55	55	46	51	50.4	42
34	49	50	46	46	43	46	52	48	41	46.8	41
35	51	48	40	47	52	51	42	40	42	45.9	40
36	46	44	40	44	47	47	43	42	44	44.1	40
37	47	40	45	50	43	41	42	43	47	44.2	40
38	42	44	47	44	49	42	43	40	46	44.1	40

Table A17. Rebound Numbers in Cells of Zone AM

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	54	52	47	45	50	51	45	49	52	49.4	45
2	50	48	47	45	41	45	45	50	42	45.9	41
3	42	53	39	42	45	48	37	36	52	43.8	36
4	55	44	47	40	40	48	44	48	42	45.4	40
5	47	40	45	43	47	50	47	45	44	45.3	40
6	47	46	36	50	42	55	40	52	50	46.4	36
7	44	43	43	45	44	45	51	49	55	46.6	43
8	44	46	46	48	41	49	53	45	52	47.1	41
9	50	43	51	52	40	41	53	53	50	48.1	40
10	45	54	49	48	53	52	54	42	45	49.1	42
11	42	42	44	43	43	45	48	53	52	45.8	42
12	50	43	56	62	49	52	53	52	46	50.3	43
13	53	51	50	44	53	48	49	47	53	49.8	44
14	60	55	44	51	49	49	41	51	52	50.2	41
15	55	55	54	51	56	54	45	48	43	51.2	43
16	50	52	55	43	50	52	51	50	46	49.9	43

Table A18. Rebound Numbers in Cells of Zone AS

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	42	56	50	48	50	52	53	51	54	50.7	48
2	55	60	58	49	50	52	53	51	48	52.9	48
3	47	56	53	56	55	49	45	43	51	50.6	43
4	57	51	56	56	58	59	49	52	53	54.6	49
5	54	59	54	56	50	55	58	53	40	53.2	40
6	42	46	48	58	50	46	46	54	50	48.9	42
7	44	46	48	51	42	42	40	52	48	45.9	40
8	52	48	52	54	48	49	43	44	43	48.1	43
9	42	54	52	53	54	52	43	42	43	48.3	42
10	54	53	44	45	46	46	56	38	50	48.0	38
11	50	48	52	43	52	61	44	48	38	48.4	43
12	58	51	54	54	51	44	50	43	50	50.6	43
13	38	49	53	50	38	53	40	45	45	45.7	38
14	42	49	45	46	46	50	50	38	45	45.7	38
15	54	56	49	49	52	50	58	54	52	52.7	49
16	51	50	48	49	47	50	51	50	54	50.0	47
17	55	45	40	48	52	43	51	54	59	49.7	40
18	40	48	44	50	51	53	51	51	51	48.9	40
19	42	50	56	43	40	48	48	52	49	47.6	40
20	51	44	41	45	53	46	50	52	61	49.2	41
21	54	56	52	45	48	48	45	40	53	49.0	40
22	49	55	54	47	48	46	54	44	53	50.0	44
23	54	40	36	54	52	48	51	51	52	50.9	46
24	57	55	50	52	51	59	50	54	50	53.1	50
25	55	55	49	54	52	49	43	43	50	50.0	43
26	59	56	56	49	53	54	52	41	49	52.1	41
27	50	38	46	54	53	56	41	47	52	48.6	38
28	44	46	44	52	44	43	53	55	40	46.8	40
29	50	47	38	47	44	51	50	40	46	45.9	38
30	36	51	47	44	49	42	48	40	43	44.4	36
31	49	51	50	51	54	48	46	52	52	50.3	44
32	56	43	54	52	50	49	52	55	54	51.7	43
33	52	44	54	46	49	44	50	48	42	47.7	42
34	48	49	40	44	44	49	44	41	38	44.1	38
35	42	40	42	47	42	43	30	38	36	40.0	30
36	rough		surface								
37	rough		surface								
38	rough		surface								

Table A19. Rebound Numbers in Cells of Zone BN

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	57	50	50	47	50	56	54	54	47	51.7	47
2	55	45	60	56	56	51	51	50	49	58.4	44
3	54	53	53	54	54	48	41	50	42	49.9	41
4	38	41	46	46	50	43	42	48	52	45.1	38
5	52	56	54	41	50	52	47	48	40	48.9	40
6	54	58	54	51	47	44	51	53	50	51.3	44
7	55	48	48	41	42	54	51	48	49	48.4	41
8	55	55	53	53	45	45	43	41	48	48.7	41
9	59	48	54	48	54	43	48	54	54	51.3	43
10	48	54	54	56	55	50	56	46	56	52.8	46
11	52	54	58	55	53	51	50	45	45	51.4	45
12	54	56	51	51	53	54	55	46	43	51.4	43
13	58	58	53	52	58	56	42	49	47	52.6	42
14	53	55	57	53	53	56	51	54	50	53.6	50
15	50	53	54	52	48	55	50	50	48	51.1	48
16	50	56	54	47	50	48	56	55	54	52.2	47
17	52	47	58	51	49	50	53	54	50	51.6	47
18	49	51	49	53	57	41	55	58	52	51.7	41
19	52	41	41	38	38	39	48	38	38	41.4	38
20	56	50	42	38	48	53	54	45	39	47.2	38
21	44	43	52	56	42	46	42	54	54	48.1	42
22	30	42	46	51	44	49	32	36	39	41.0	30
23	40	30	40	49	47	42	40	40	44	41.3	30
24	46	44	36	43	45	38	50	44	36	42.4	36
25	54	43	36	40	54	56	45	45	50	47.0	36
26	54	53	57	46	46	50	49	48	43	49.6	43
27	54	54	54	51	55	56	50	44	49	51.9	44
28	58	58	56	55	55	55	54	51	47	54.3	47
29	58	57	56	55	60	58	47	47	53	54.6	47
30	59	55	52	60	56	53	40	42	44	51.2	40
31	40	54	52	46	49	56	58	42	57	50.4	40
32	38	41	41	56	53	56	53	55	54	49.7	38
33	57	49	54	52	53	55	54	60	54	54.2	49
34	46	53	52	60	56	52	53	52	54	53.1	46
35	52	48	42	51	51	53	54	46	54	50.1	42
36	54	50	52	56	51	44	52	51	46	50.7	44
37	54	50	52	55	47	51	53	50	47	51.7	47
38	45	48	53	53	50	43	47	43	52	48.2	43

Table A20. Rebound Numbers in Cells of Zone BM

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	45	55	51	54	56	57	53	48	54	42.6	45
2	50	52	49	54	54	58	46	40	50	50.3	40
3	56	46	50	55	54	55	44	50	45	50.6	44
4	49	42	49	52	53	52	42	45	40	47.1	40
5	52	50	53	51	50	48	40	46	45	48.3	40
6	51	51	49	45	53	51	41	48	48	48.6	41
7	53	46	44	47	43	53	45	46	51	47.6	43
8	48	52	42	55	51	52	49	46	48	49.2	42
9	54	54	44	51	55	48	46	54	53	51.0	44
10	52	45	44	52	52	54	49	57	53	50.9	44
11	51	43	47	41	54	41	57	48	47	47.7	41
12	51	53	45	49	53	45	44	51	51	49.1	44
13	52	47	51	52	50	48	53	54	50	50.8	47
14	50	46	52	48	50	51	55	50	47	49.9	46
15	50	50	54	51	48	55	50	49	55	51.3	48
16	47	52	48	43	45	51	52	48	48	42.9	43

Table A21. Rebound Numbers in Cells of Zone BS

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	47	49	51	52	40	41	50	52	46	47.6	40
2	42	49	40	48	48	45	40	47	41	44.4	40
3	38	50	53	42	38	48	48	40	40	44.1	38
4	40	46	40	38	56	44	44	49	51	45.3	38
5	43	37	43	33	44	44	50	53	44	43.4	33
6	51	38	39	40	37	52	48	46	50	44.6	37
7	51	42	49	46	44	44	40	38	46	44.4	38
8	41	49	46	49	44	46	47	45	53	46.7	41
9	42	43	49	46	42	42	43	44	38	43.2	42
10	50	46	45	44	41	51	47	57	49	47.8	41
11	48	45	45	41	48	41	49	41	47	45.0	41
12	46	52	45	42	46	45	38	46	44	44.9	38
13	52	49	42	46	38	43	47	50	52	46.6	38
14	56	40	50	48	47	42	52	52	42	47.7	40
15	55	48	47	46	50	45	50	40	43	47.1	40
16	52	52	52	42	50	43	50	43	52	48.4	42
17	48	59	56	52	56	46	42	54	46	51.0	42
18	59	52	46	52	45	52	52	54	50	51.3	46
19	54	44	48	53	45	48	44	38	51	47.2	44
20	50	51	50	48	54	54	54	53	54	52.0	48
21	45	51	44	50	46	47	54	48	50	48.3	44
22	50	50	38	52	54	48	55	52	42	49.0	38
23	40	43	53	49	48	37	48	45	47	45.6	37
24	51	51	43	42	53	45	49	50	36	46.7	36
25	51	44	53	50	54	42	45	44	44	47.4	42
26	54	52	52	56	42	40	41	48	41	47.3	40
27	58	40	42	44	46	52	36	42	42	44.4	36
28	41	41	39	43	49	53	39	41	36	42.4	36
29	40	36	34	43	36	46	42	42	40	40.6	34
30	37	37	38	42	46	40	37	38	40	39.2	37
31	46	48	42	48	50	42	44	53	45	46.4	42
32	40	42	46	40	45	52	50	48	48	45.7	40
33	52	52	50	44	47	43	42	44	40	46.0	40
34	42	46	52	52	40	41	41	47	45	45.1	40
35	40	38	42	38	38	40	44	39	40	39.9	38
36	30	36	40	38	42	37	32	36	40	36.8	30
37	40	31	30	40	36	46	38	42	52	40.1	30
38	38	40	46	38	30	42	38	34	37	38.1	30

Table A22. Rebound Numbers in Cells of Zone CN

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	37	42	50	45	52	48	47	42	47	45.6	37
2	42	46	38	40	42	48	48	48	46	44.2	38
3	41	54	34	51	50	50	49	54	50	48.1	34
4	39	48	51	44	39	41	50	50	50	45.8	39
5	44	50	46	48	37	37	46	50	42	44.4	37
6	53	46	50	39	40	37	41	52	50	45.3	37
7	41	45	38	40	38	32	47	40	43	40.4	32
8	52	51	49	48	48	50	43	34	52	47.4	34
9	42	45	45	32	46	43	48	54	54	45.4	32
10	48	53	45	43	45	37	38	51	49	45.4	37
11	54	47	40	49	48	42	41	49	51	46.8	41
12	42	53	42	40	37	41	45	47	51	44.2	37
13	42	50	50	43	39	46	50	49	47	46.2	39
14	39	40	46	51	41	48	48	45	37	43.9	37
15	48	54	39	51	49	52	46	47	35	46.8	35
16	42	48	48	53	50	36	52	44	48	46.8	36
17	42	42	51	48	38	40	50	52	46	45.4	38
18	40	50	54	40	48	44	51	50	51	47.6	46
19	42	47	41	46	50	48	46	50	51	46.8	46
20	44	50	43	41	46	55	51	52	49	47.9	41
21	52	51	45	49	41	55	45	45	45	47.6	41
22	47	51	50	51	51	53	53	50	45	50.1	45
23	43	50	45	51	52	49	53	54	55	50.2	43
24	39	42	47	51	52	51	52	48	44	47.3	39
25	39	41	40	54	43	42	50	50	46	45.0	39
26	32	30	38	50	42	43	50	50	51	42.9	30
27	48	39	36	50	51	53	52	46	52	47.4	36
28	52	49	50	51	49	51	41	49	52	49.3	41
29	48	45	52	48	45	41	42	40	48	45.4	40
30	50	32	44	38	51	48	52	45	40	44.4	32
31	43	49	40	51	44	42	33	40	34	41.8	33
32	51	40	41	48	52	42	42	40	38	43.8	38
33	52	55	40	37	40	50	53	48	53	46.4	40
34	51	52	47	50	43	52	41	48	38	46.9	38
35	51	50	48	54	54	54	51	41	53	50.7	41
36	53	38	38	40	46	53	52	52	38	45.6	38
37	45	45	41	50	54	47	47	54	51	48.2	41
38	50	49	53	41	48	50	52	39	50	48.0	39

Table A23. Rebound Numbers in Cells of Zone CM

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	47	50	49	55	43	52	56	54	55	51.2	43
2	51	51	46	50	50	58	60	55	55	52.9	46
3	44	41	54	54	44	50	54	53	57	50.1	41
4	48	45	50	46	50	50	56	48	59	50.2	45
5	53	51	55	55	51	42	56	52	54	52.1	42
6	53	57	48	54	44	55	54	41	57	51.4	41
7	50	51	40	39	51	45	52	54	48	47.8	39
8	55	52	55	48	44	47	48	56	55	51.1	44
9	47	47	45	48	46	46	52	40	53	47.1	40
10	45	55	51	54	44	51	50	47	41	48.7	41
11	48	52	44	49	53	55	49	51	53	50.4	44
12	58	52	53	48	49	44	54	55	53	51.8	44
13	46	57	52	59	53	53	42	50	48	51.1	42
14	51	42	44	54	48	49	41	51	48	47.6	41
15	59	58	50	56	52	53	55	44	52	53.2	44
16	53	54	52	53	47	49	48	40	52	49.8	40

Table A24. Rebound Numbers in Cells of Zone CS

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	55	52	52	48	52	49	48	50	53	51.0	48
2	56	54	50	50	57	54	52	53	49	52.8	49
3	55	46	51	52	45	47	53	48	52	49.9	45
4	51	52	54	39	49	42	44	50	52	48.1	39
5	39	42	48	46	34	36	51	50	52	44.2	34
6	40	42	49	42	45	52	52	56	42	46.7	40
7	56	48	42	40	42	51	50	50	34	45.9	34
8	50	49	53	53	51	47	48	40	46	48.6	40
9	47	56	52	42	44	45	38	44	50	46.4	38
10	44	39	52	50	43	54	32	34	46	43.8	32
11	50	52	39	47	40	49	48	50	45	46.7	39
12	50	51	43	51	48	47	47	46	42	47.2	42
13	54	47	46	52	47	52	50	41	40	47.8	40
14	49	48	55	51	55	52	40	37	50	48.6	37
15	54	49	52	48	44	51	40	43	38	46.6	38
16	48	45	48	54	46	46	42	36	48	45.9	36
17	41	36	48	47	46	40	45	51	50	44.9	36
18	36	42	43	42	40	42	50	52	44	43.4	36
19	39	42	50	47	42	47	44	40	49	44.4	39
20	48	40	49	54	55	42	44	48	47	47.4	40
21	54	51	49	53	52	54	47	40	54	50.4	40
22	47	56	40	47	45	55	53	44	38	47.2	38
23	43	47	39	49	54	48	43	51	48	46.9	39
24	47	53	45	45	49	52	50	51	51	49.2	45
25	52	44	38	51	52	51	52	51	55	49.6	38
26	43	43	42	52	48	49	52	48	54	47.9	42
27	45	41	42	42	49	48	50	41	50	45.3	41
28	39	37	42	36	48	36	49	51	40	42.0	36
29	43	53	39	51	49	40	47	53	50	47.2	39
30	45	46	48	51	50	42	54	55	55	49.6	42
31	47	47	50	51	52	48	55	57	54	51.2	47
32	48	50	52	53	55	50	58	56	53	52.8	48
33	52	42	50	40	39	46	45	41	40	43.9	40
34	50	48	49	46	47	53	53	50	50	49.6	47
35	50	55	52	46	46	47	45	50	50	49.0	46
36	34	40	42	41	40	40	50	52	42	42.3	34
37	40	34	39	42	39	40	40	41	39	39.3	34
38	36	34	35	40	38	35	31	37	38	36.0	31

Table A25. Rebound Numbers in Cells of Zone DN

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	42	38	42	40	51	41	43	42	40	42.1	38
2	40	40	52	44	36	43	40	38	46	42.1	36
3	51	45	50	41	40	34	47	41	48	44.1	34
4	46	50	48	50	41	38	46	46	38	44.8	38
5	51	52	52	40	48	48	43	46	44	53.0	40
6	53	50	43	50	46	40	49	50	46	47.4	40
7	49	39	55	47	50	48	49	49	48	48.2	39
8	51	48	50	53	45	47	55	48	50	49.7	45
9	48	45	47	43	51	44	47	53	45	47.0	43
10	47	46	47	42	47	48	48	48	51	47.2	43
11	48	47	53	43	51	46	47	44	51	47.8	43
12	49	51	44	52	38	51	49	43	49	47.3	38
13	51	47	49	51	46	48	42	41	45	46.7	41
14	50	48	51	42	37	37	36	38	37	41.8	36
15	50	42	48	46	45	36	39	48	45	44.3	36
16	41	50	41	50	37	38	49	47	45	44.2	38
17	56	54	50	43	52	52	54	51	49	51.2	43
18	50	49	55	61	52	49	53	51	53	52.6	49
19	52	51	54	48	50	47	49	53	56	51.1	47
20	62	53	47	48	46	48	44	54	49	50.1	46
21	43	53	57	54	49	51	53	41	51	50.2	41
22	50	52	54	54	51	50	57	41	50	51.0	41
23	55	53	52	51	50	42	42	58	50	50.3	42
24	52	51	48	47	52	49	46	46	52	49.2	46
25	52	48	52	55	51	48	43	56	50	50.6	43
26	53	60	56	56	53	51	43	50	41	51.4	41
27	52	49	54	44	43	41	53	46	59	46.4	40
28	40	53	51	44	43	40	48	40	54	45.9	40
29	47	50	49	47	40	48	55	47	43	47.3	40
30	56	52	51	50	41	46	51	49	50	49.6	41
31	53	46	55	47	48	43	42	46	52	48.0	42
32	49	47	54	48	46	57	50	36	39	47.3	36
33	48	42	46	30	47	47	40	50	46	44.0	30
34	48	48	38	42	42	42	41	45	49	43.9	38
35	41	42	46	30	43	55	55	49	42	47.0	41
36	52	51	47	48	53	49	41	45	40	47.3	40
37	49	47	43	35	48	49	40	48	50	45.4	35
38	48	48	36	47	53	52	54	51	48	48.6	36

Table A26. Rebound Numbers in Cells of Zone DM

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	53	55	52	50	49	53	65	56	60	54.8	49
2	54	53	56	53	55	45	54	53	54	53.0	45
3	49	57	54	55	52	56	43	54	53	52.6	43
4	51	56	55	50	54	54	47	56	54	53.0	47
5	57	50	56	54	53	52	51	55	57	53.9	50
6	56	58	45	50	49	53	53	50	46	51.1	45
7	53	57	47	52	55	55	58	42	48	51.9	42
8	57	57	51	58	54	47	54	56	54	54.2	47
9	58	57	52	54	59	53	52	56	44	53.9	44
10	58	44	51	58	55	55	57	54	46	52.4	40
11	51	55	53	56	47	49	53	53	52	52.0	47
12	52	56	56	60	48	55	49	51	51	53.2	48
13	54	56	53	50	56	41	48	48	41	49.7	41
14	58	52	40	41	47	49	56	60	51	50.4	40
15	44	56	53	54	49	49	47	55	56	51.4	44
16	52	57	53	44	58	52	52	55	40	51.4	40

Table A27. Rebound Numbers in Cells of Zone DS

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	34	48	52	47	44	44	51	47	50	46.3	34
2	48	44	45	39	38	42	52	46	48	44.7	38
3	40	48	44	43	48	39	48	47	49	45.1	39
4	46	38	43	45	42	45	52	49	50	45.6	38
5	45	48	48	45	47	43	43	49	48	46.2	43
6	36	43	40	40	43	44	47	41	45	42.1	36
7	44	52	50	39	42	36	42	47	51	44.8	36
8	49	48	40	36	45	39	47	50	38	43.6	36
9	50	46	53	42	39	37	37	45	48	44.1	37
10	50	40	49	38	40	42	44	38	45	42.9	38
11	54	55	50	41	10	39	43	47	44	45.9	39
12	46	50	55	55	47	48	50	47	40	48.7	40
13	45	48	46	47	49	54	48	39	46	46.9	39
14	50	41	51	54	50	39	43	39	38	45.0	38
15	44	51	42	37	49	52	36	43	40	43.8	36
16	48	37	41	52	53	49	56	55	53	49.3	37
17	53	54	54	38	53	49	48	40	49	48.7	38
18	56	55	54	48	55	49	44	40	52	50.3	40
19	50	46	51	48	49	50	43	50	42	47.7	42
20	47	47	50	52	53	49	53	50	54	50.6	47
21	47	53	50	55	48	49	52	49	54	50.8	47
22	44	50	45	55	45	54	51	54	32	47.8	32
23	42	42	48	49	48	46	43	42	38	44.7	38
24	50	47	54	53	47	54	43	42	50	48.9	42
25	53	50	53	46	43	48	51	57	57	50.9	43
26	51	51	54	43	45	49	52	46	40	47.9	40
27	53	50	46	39	45	44	51	39	40	45.1	38
28	47	51	53	51	41	49	40	36	48	46.2	36
29	48	42	53	51	46	46	46	36	45	45.9	36
30	49	53	51	49	52	50	48	54	48	50.4	48
31	44	40	52	50	43	50	49	43	41	45.8	40
32	50	41	46	45	39	39	40	52	53	45.0	39
33	51	51	41	56	49	49	50	48	56	50.1	48
34	50	48	46	48	51	45	48	44	40	46.7	40
35	51	54	48	48	47	45	48	41	40	46.9	45
36	47	46	45	47	45	47	48	48	52	47.0	45
37	39	49	50	44	50	36	49	50	41	45.3	36
38	49	38	40	38	39	41	50	45	51	43.4	38

Table A28. Rebound Numbers in Cells of Zone EN

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	37	44	39	49	42	44	44	42	42	42.6	37
2	52	42	42	42	47	46	44	42	38	43.9	38
3	40	46	54	52	44	51	43	42	42	46.0	40
4	52	49	41	52	49	50	48	43	44	47.6	41
5	54	45	48	46	53	60	48	42	38	48.2	38
6	46	57	54	53	46	48	50	42	44	48.9	42
7	48	50	48	46	52	50	44	46	48	48.0	44
8	50	43	46	54	46	39	52	50	50	47.8	39
9	47	50	41	41	45	50	50	44	45	47.0	41
10	51	40	42	47	39	47	52	44	43	45.0	39
11	48	44	44	46	47	40	42	43	45	44.3	40
12	40	40	43	52	38	40	46	44	44	43.0	38
13	42	46	38	42	42	40	49	42	48	43.2	38
14	52	42	42	40	44	40	45	42	50	44.1	40
15	50	52	50	38	40	46	46	41	40	44.8	38
16	42	50	46	46	47	50	47	49	48	47.2	42
17	41	46	42	36	47	35	42	46	46	42.3	36
18	46	48	42	38	40	39	38	42	48	42.3	38
19	48	52	50	47	49	41	44	50	56	48.6	41
20	50	47	45	47	47	47	53	44	45	47.2	44
21	51	51	53	51	42	47	38	42	43	46.4	38
22	50	53	49	49	46	43	49	47	47	48.1	43
23	43	52	52	51	44	42	46	38	46	46.0	38
24	52	52	50	36	54	49	44	40	42	46.6	36
25	54	53	49	49	53	45	38	50	40	47.9	38
26	43	45	45	50	40	40	40	46	48	44.1	40
27	54	48	45	44	40	54	40	42	42	45.4	40
28	48	50	48	46	52	41	47	51	47	47.8	41
29	52	47	54	48	47	51	47	44	40	47.8	40
30	44	46	54	48	54	54	46	40	50	48.4	40
31	49	56	52	50	50	48	50	39	54	49.8	39
32	48	48	48	51	50	52	41	42	44	47.1	41
33	52	50	53	54	52	51	50	50	53	51.7	50
34	44	44	54	49	43	48	45	52	49	47.6	43
35	43	47	42	52	46	56	43	49	56	48.2	42
36	48	46	38	48	47	47	43	42	45	44.9	38
37	48	51	48	51	48	46	39	44	46	46.8	39
38	52	43	45	50	53	52	48	52	43	48.7	43

Table A29. Rebound Numbers in Cells of Zone EM

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	43	49	46	48	54	55	54	54	52	50.6	46
2	51	44	53	47	38	45	44	52	49	47.3	38
3	51	48	54	48	46	50	46	50	52	49.4	46
4	58	41	50	53	40	43	45	49	44	47.0	40
5	52	49	47	47	41	45	50	42	44	46.3	41
6	51	42	48	52	48	43	42	43	46	46.1	42
7	50	45	51	54	43	52	51	53	57	50.7	43
8	49	43	49	52	43	50	43	49	52	47.8	43
9	41	51	41	45	50	50	50	53	48	47.7	41
10	55	59	39	52	51	42	45	46	42	47.9	39
11	49	49	42	50	51	40	56	53	50	48.9	40
12	45	42	42	53	52	47	44	52	48	47.2	42
13	51	54	54	48	44	54	46	50	45	49.6	44
14	53	49	55	46	56	54	44	46	49	50.2	44
15	54	48	51	52	53	41	46	43	44	48.0	41
16	60	53	57	53	50	52	44	40	46	50.6	40

Table A30. Rebound Numbers in Cells of Zone ES

Point Number	Rebound Number										
	1	2	3	4	5	6	7	8	9	Mean	Minim.
1	47	40	40	42	39	41	43	40	45	41.9	39
2	48	51	45	36	38	38	36	37	40	41.0	36
3	38	41	40	37	37	38	41	41	45	39.8	37
4	36	41	47	40	42	45	52	50	49	44.7	36
5	40	49	47	45	46	39	53	40	52	45.7	39
6	50	40	50	43	49	49	51	55	53	48.9	48
7	53	51	44	41	42	52	54	49	53	48.8	41
8	48	41	53	52	52	50	48	54	53	50.1	41
9	47	50	48	51	47	50	50	53	49	49.4	47
10	5.	54	48	51	48	50	51	51	52	50.9	48
11	49	52	52	51	49	53	53	48	51	50.9	48
12	50	44	52	50	48	44	51	44	49	48.0	44
13	51	50	50	49	51	52	43	44	49	48.8	43
14	51	51	48	51	10	50	52	41	46	47.8	40
15	52	43	42	52	49	49	41	46	42	46.2	41
16	55	41	52	46	54	50	52	42	38	47.8	38
17	48	51	50	42	40	53	52	50	54	48.9	40
18	54	50	55	56	54	50	58	52	52	53.4	50
19	47	54	54	53	40	56	44	57	54	51.0	40
20	52	51	52	44	41	54	60	39	54	49.7	39
21	47	50	52	50	49	44	52	46	49	49.9	44
22	56	45	53	47	38	48	47	49	44	47.4	38
23	53	50	45	44	46	48	45	47	49	47.4	44
24	55	52	52	48	46	47	55	54	46	50.6	46
25	33	44	42	50	57	51	53	50	50	47.8	42
26	48	49	36	51	50	52	41	48	50	47.2	36
27	55	50	48	49	51	46	36	47	48	47.8	36
28	44	48	52	45	49	52	38	39	37	44.9	37
29	47	51	55	51	49	53	49	39	54	49.8	39
30	50	53	49	44	51	50	43	43	46	47.7	44
31	49	51	50	50	50	46	42	40	38	46.2	38
32	45	54	54	53	42	51	42	46	48	48.3	42
33	50	50	48	34	43	56	37	40	44	44.7	34
34	50	40	38	50	53	38	47	39	51	45.1	38
35	37	48	37	40	52	44	46	46	43	43.7	37
36	38	37	38	52	50	45	43	36	41	42.2	36
37	41	48	44	36	52	49	44	50	45	45.4	36
38	47	37	40	41	37	40	52	44	45	42.9	37

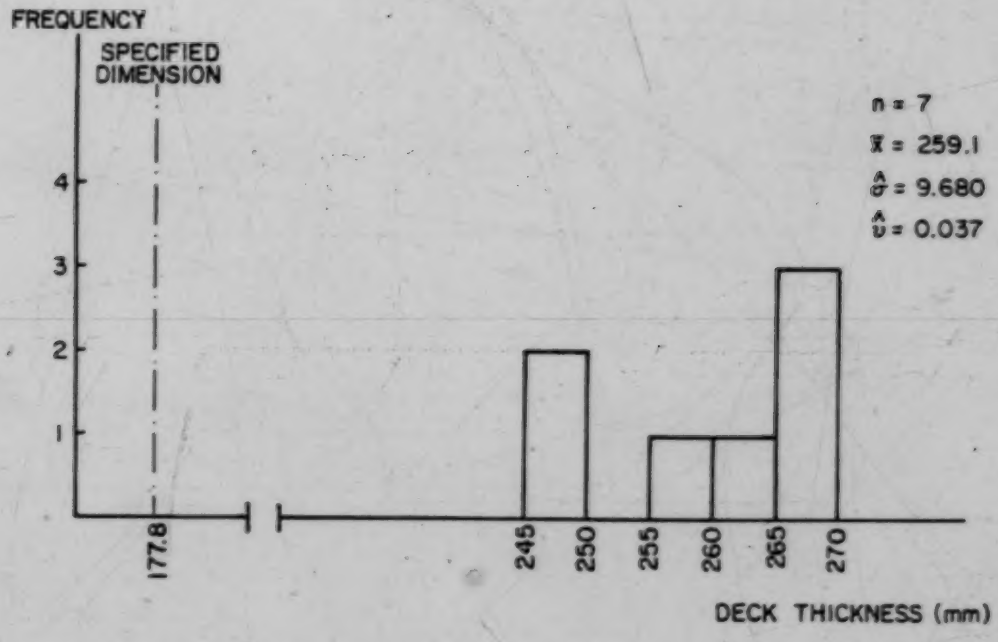
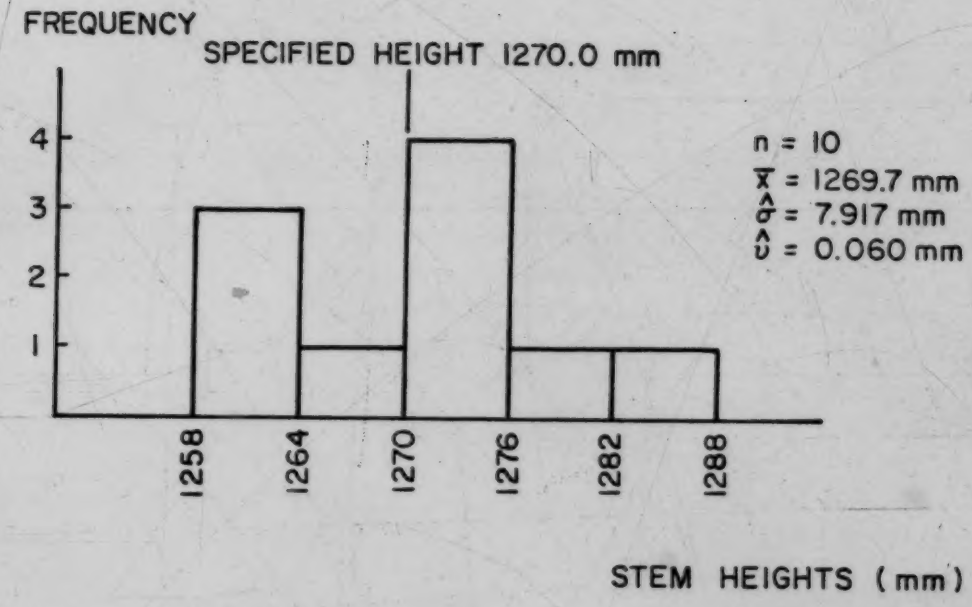


Fig. A1 Histogram of Deck Thicknesses



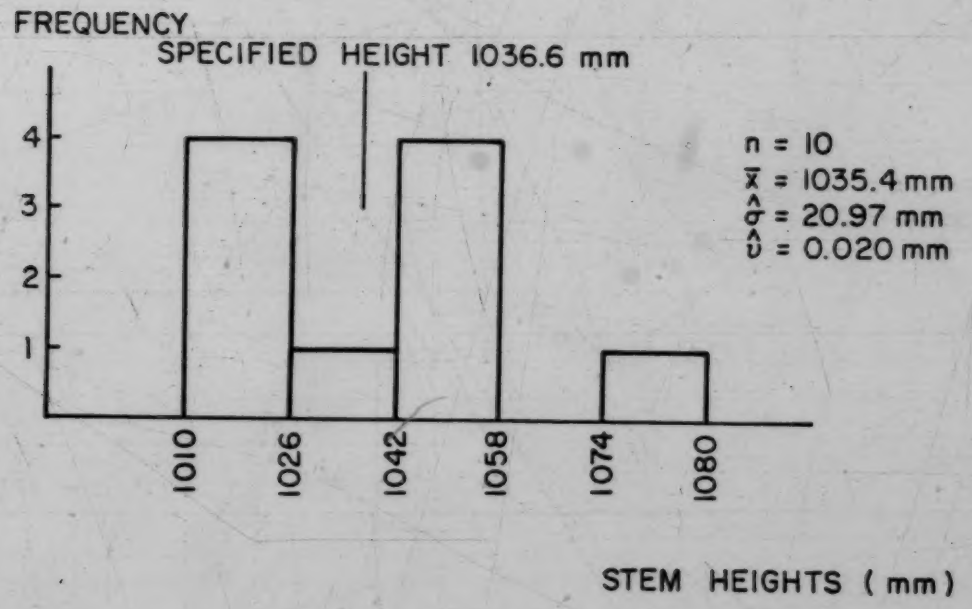
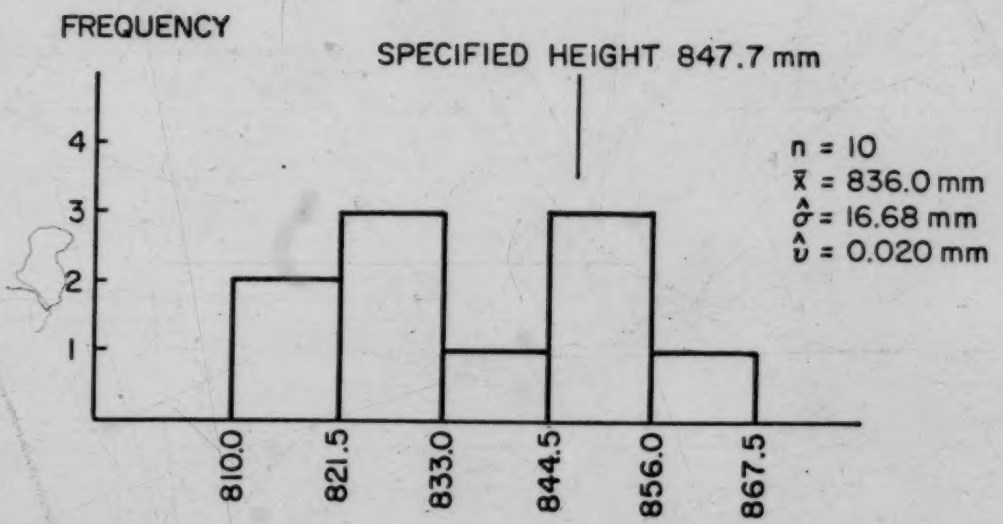


Fig. A2 Histograms of Stem Heights with Specified Values 1270.0 mm and 1036.6 mm



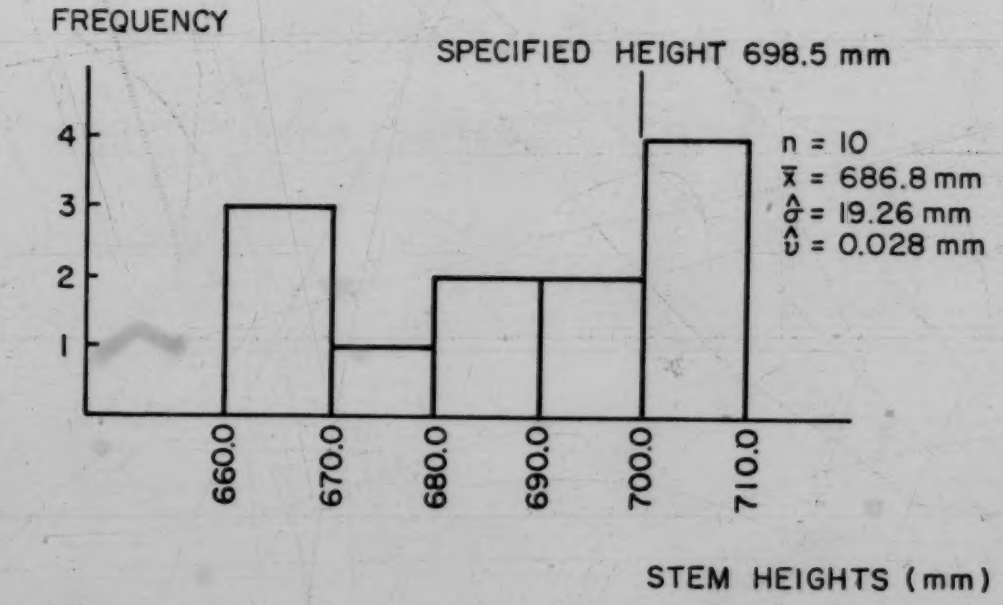
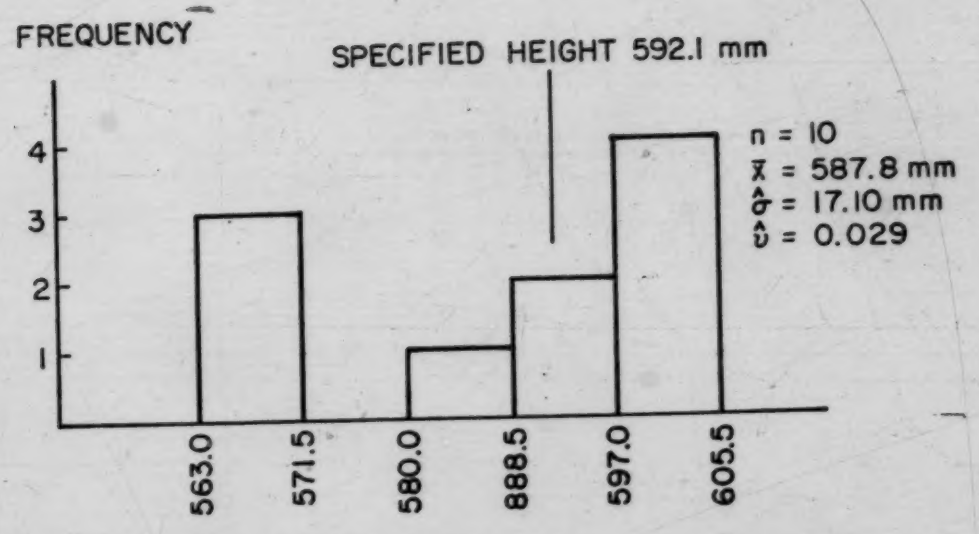


Fig. A3 Histograms of Stem Heights with Specified Values 847.7 mm and 698.5 mm



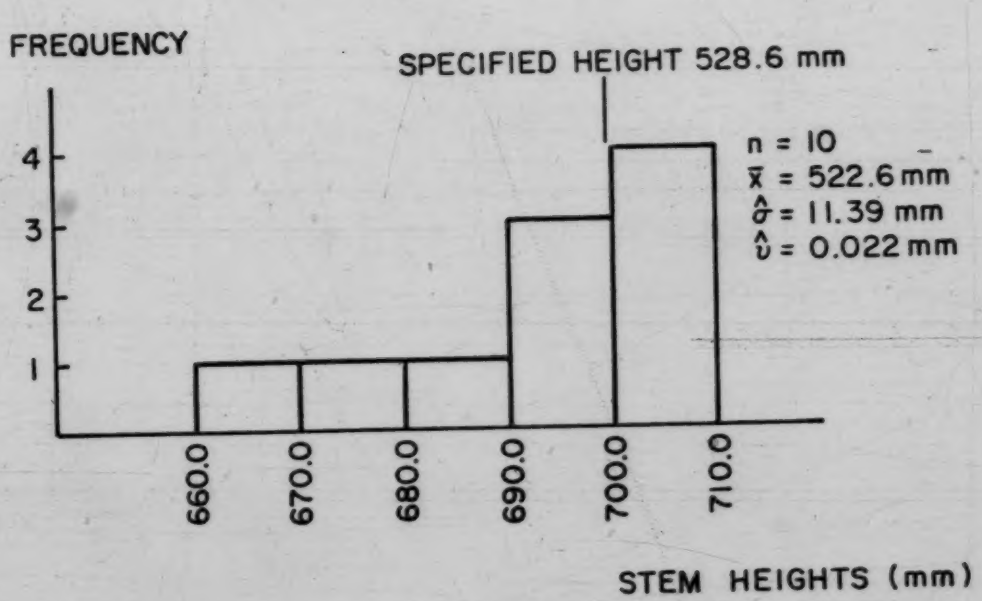


Fig. A4 Histograms of Stem Heights with Specified Values 592.1 mm and 528.6 mm

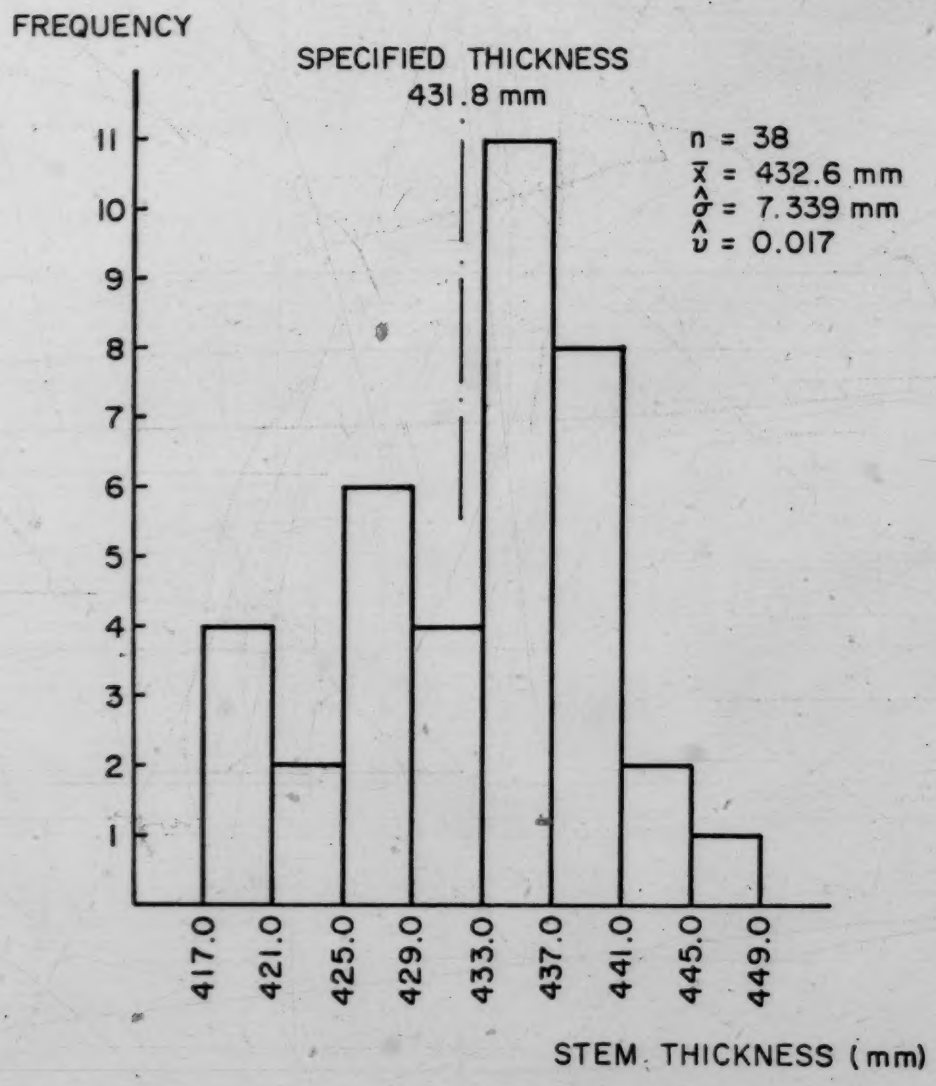


Fig. A5 Histogram of Stem Thicknesses in Zone AN

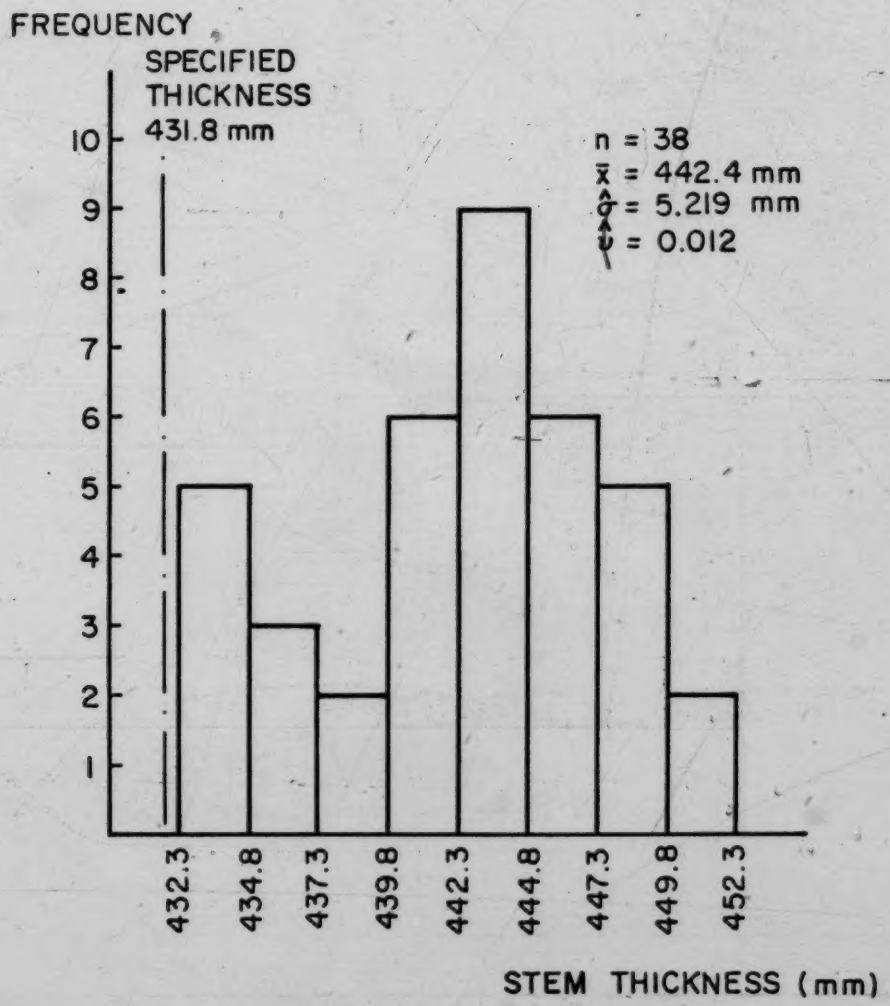


Fig. A6 Histogram of Stem Thicknesses in Zone AM

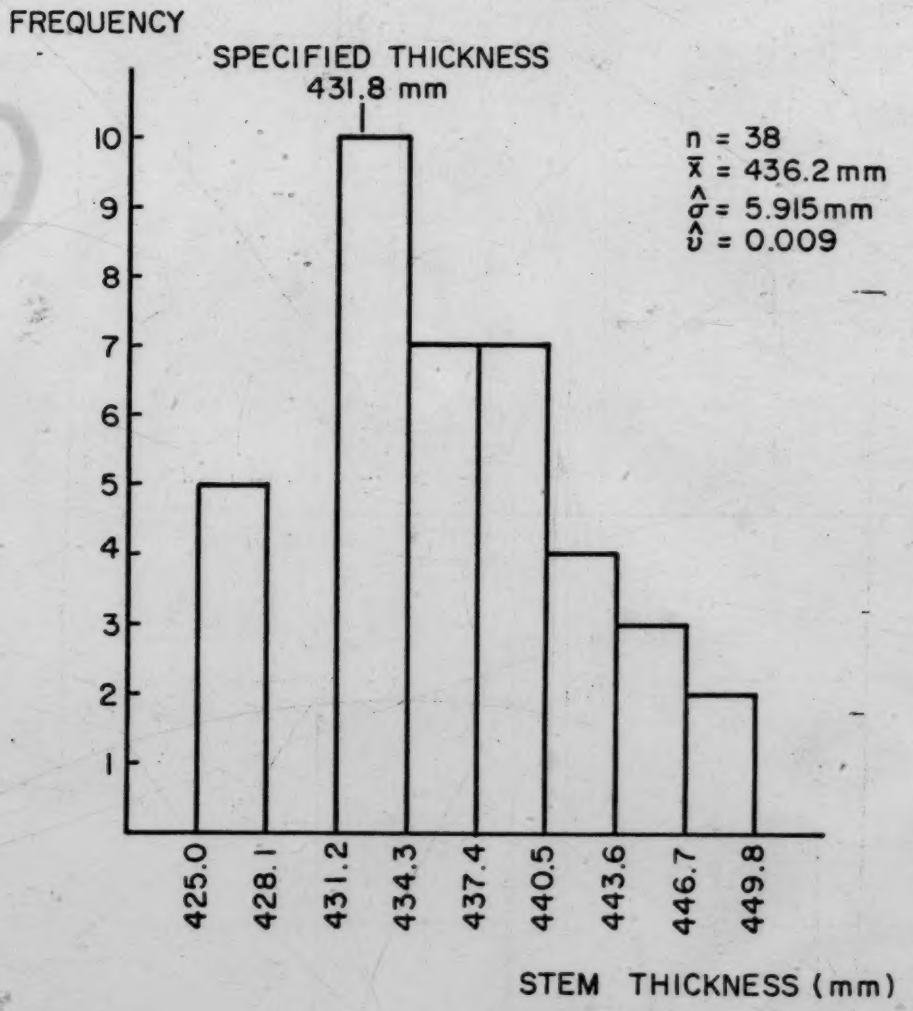


Fig. A7 Histogram of Stem Thicknesses in Zone AS

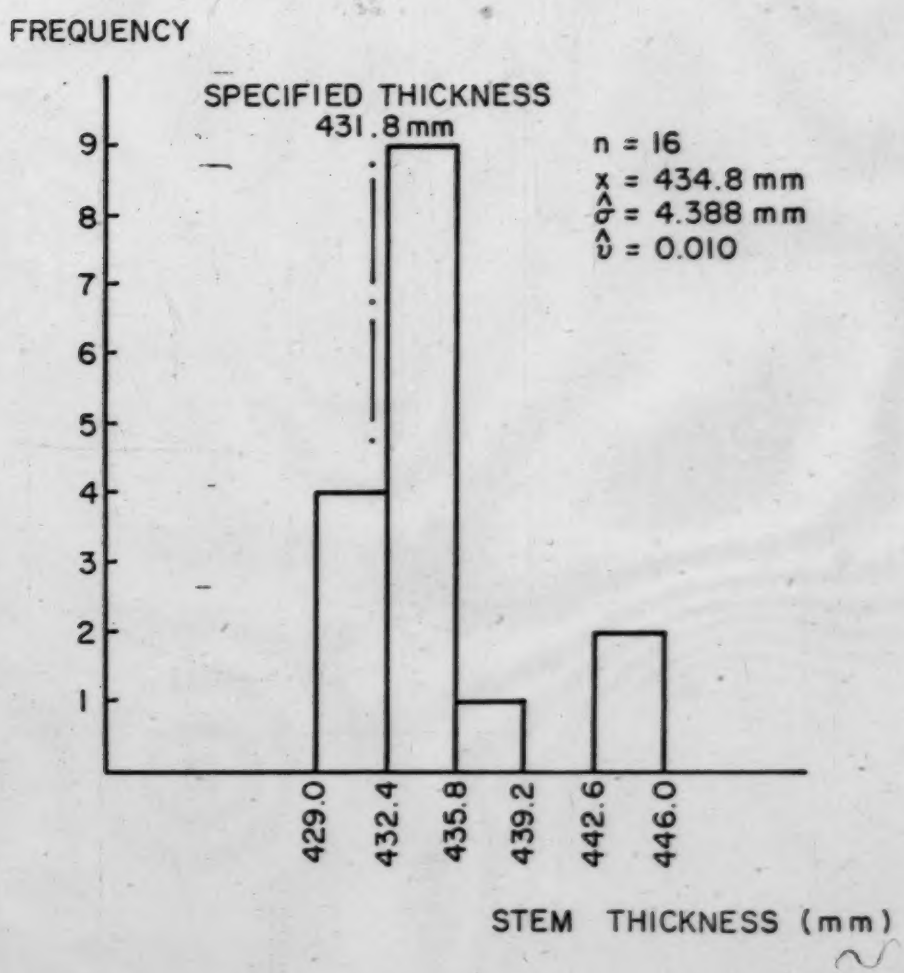


Fig. A8 Histogram of Stem Thicknesses in Zone BN

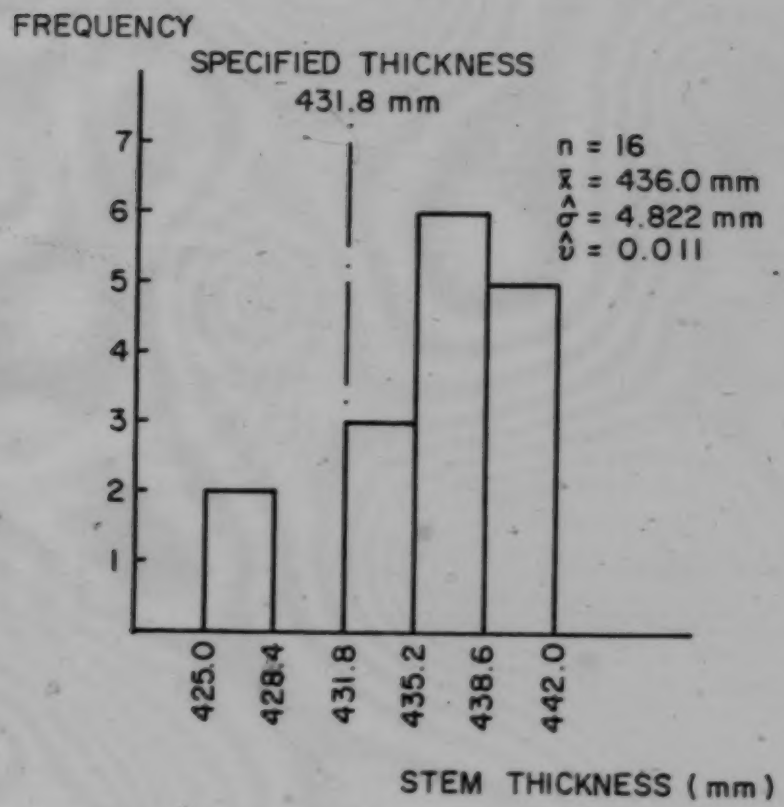


Fig. A9 Histogram of Stem Thicknesses in Zone BM

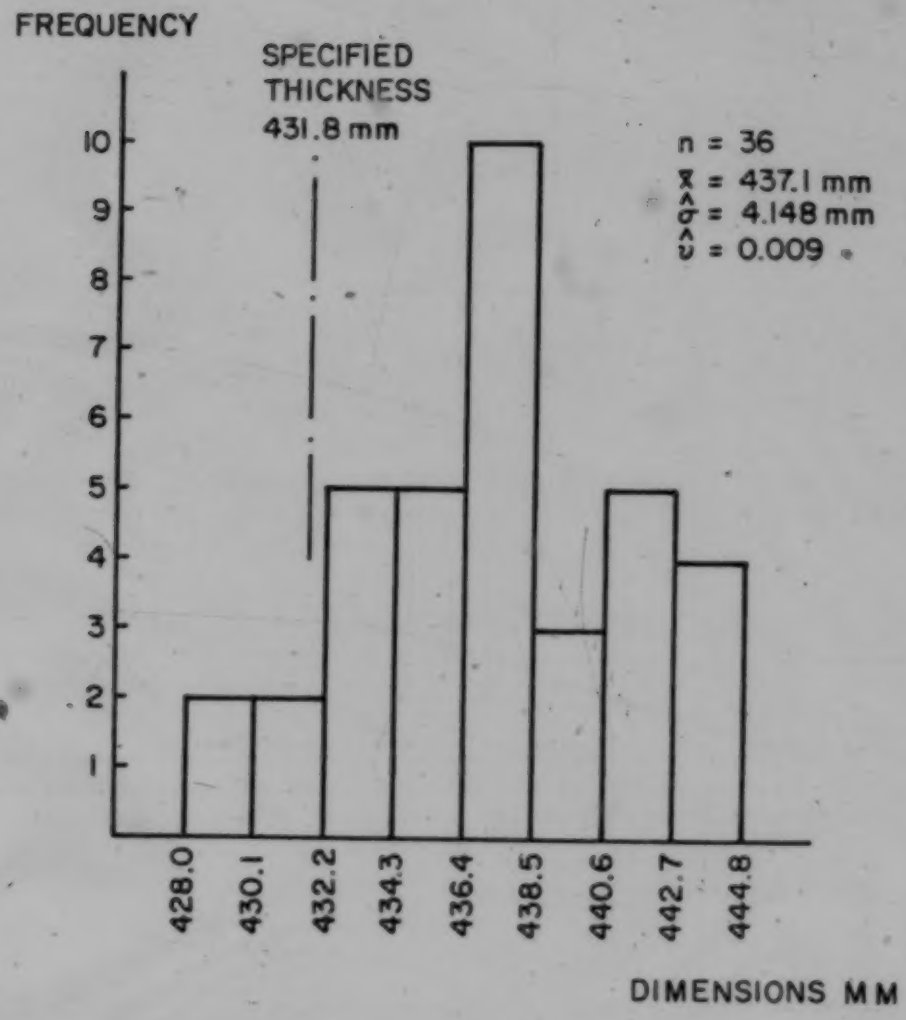


Fig. A10 Histogram of Stem Thicknesses in Zone BS

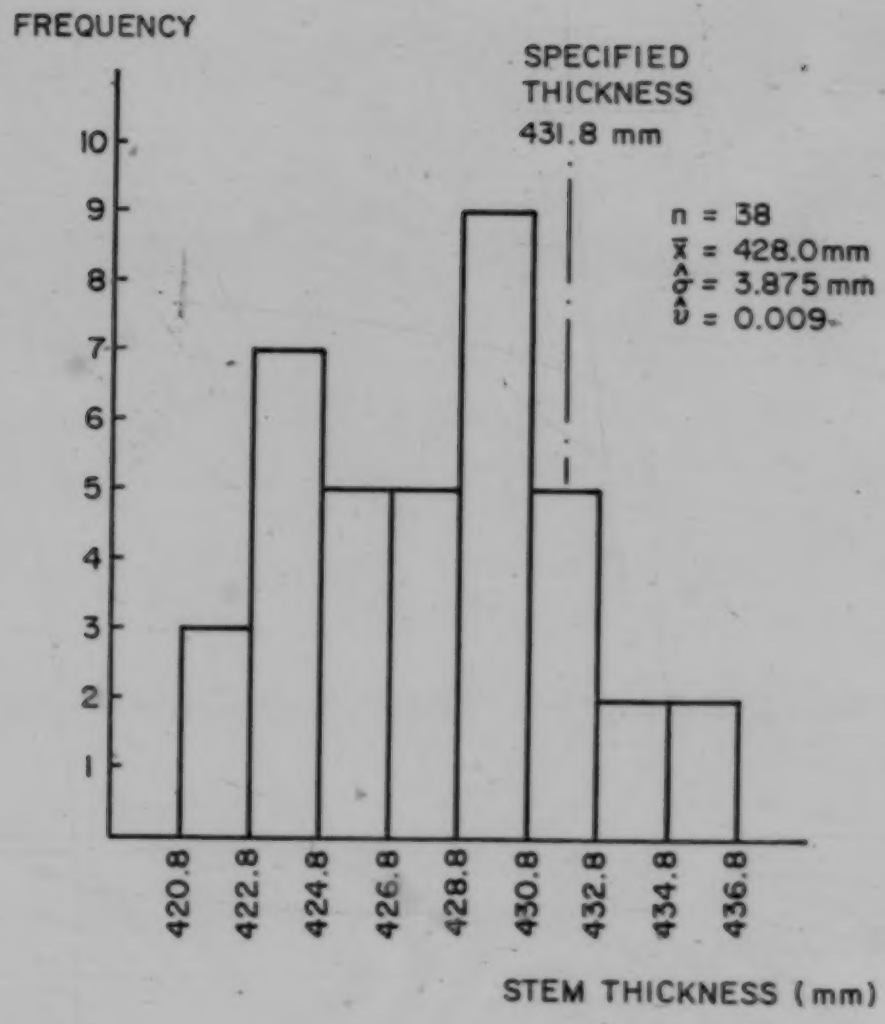


Fig. A11 Histogram of Stem Thicknesses in Zone CN

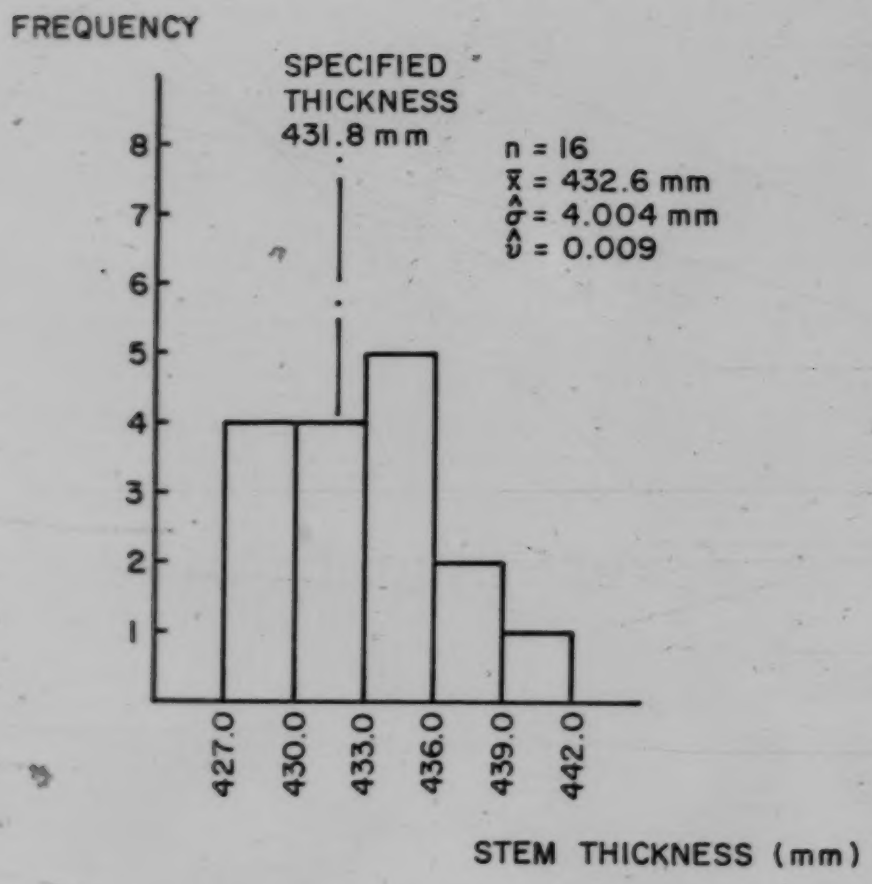


Fig. A12 Histogram of Stem Thicknesses in Zone CM

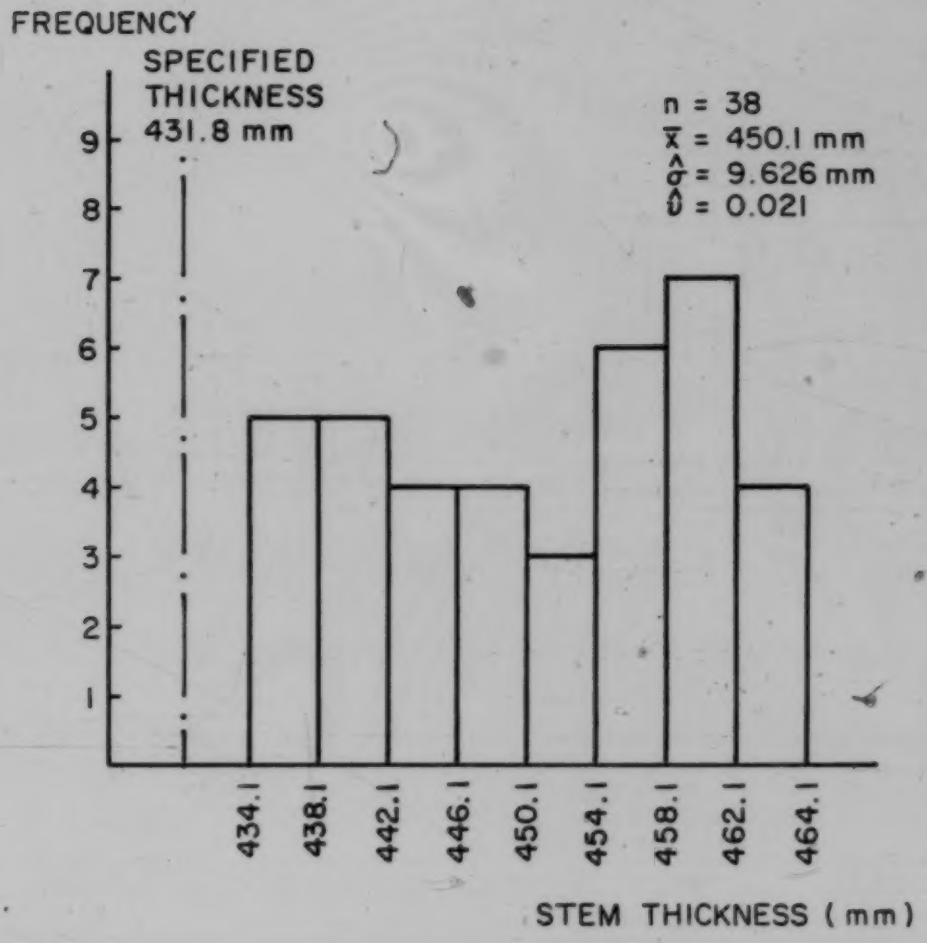


Fig. A13 Histogram of Stem Thicknesses in Zone CS

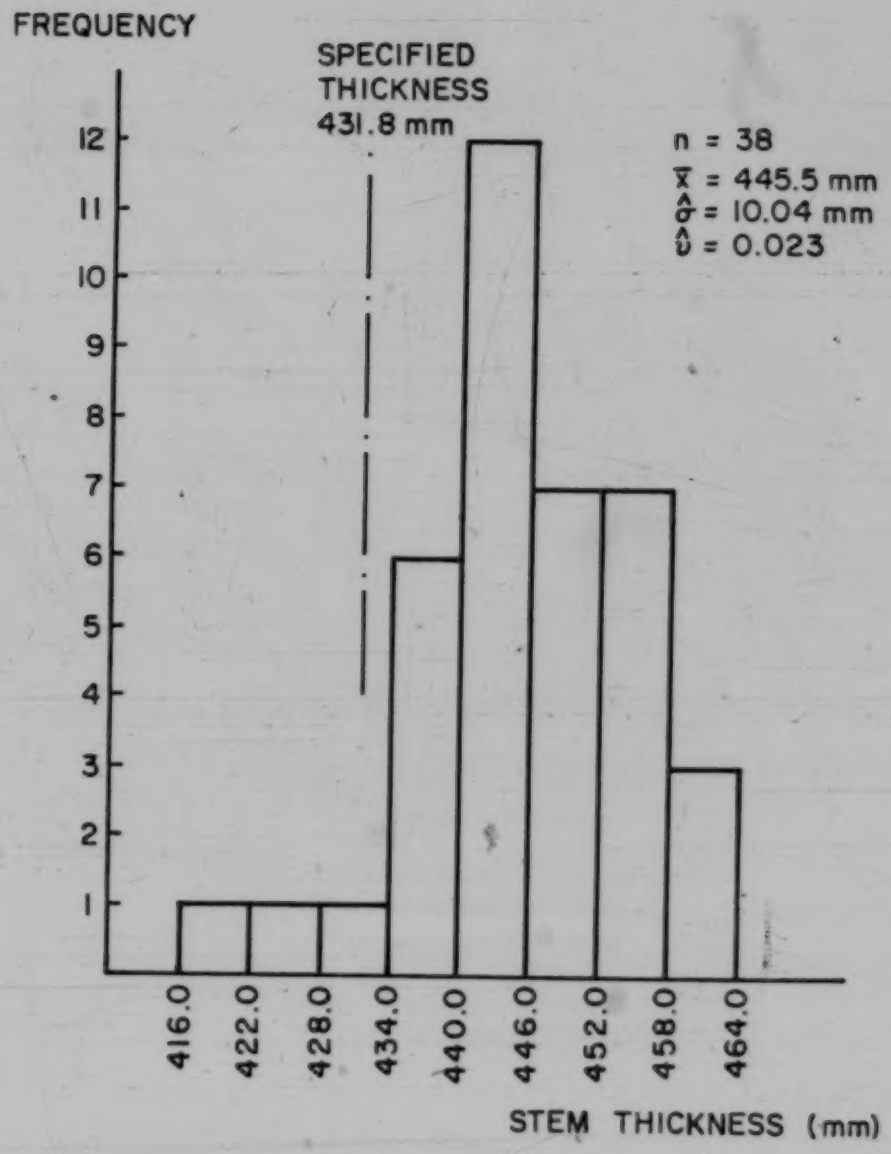


Fig. A14 Histogram of Stem Thicknesses in Zone DN

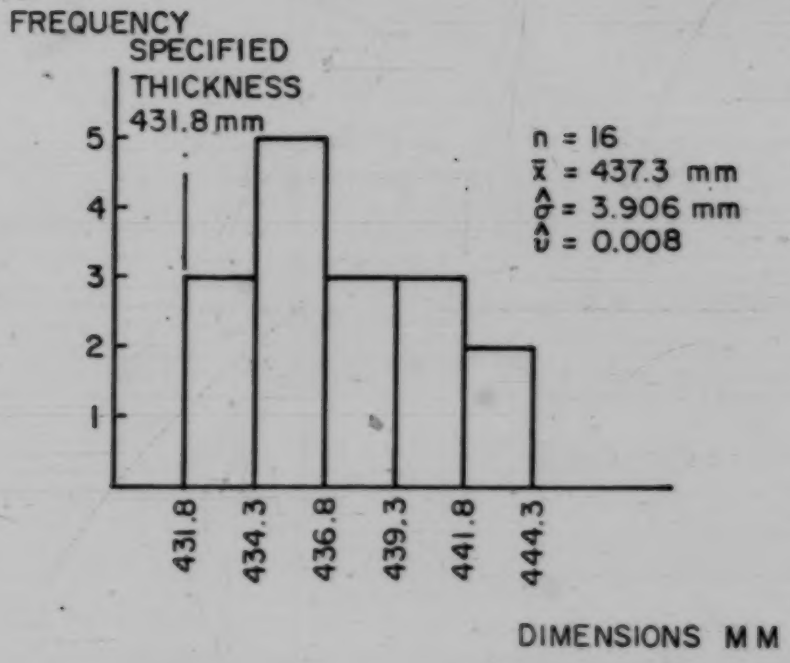


Fig. A15 Histogram of Stem Thicknesses in Zone DM

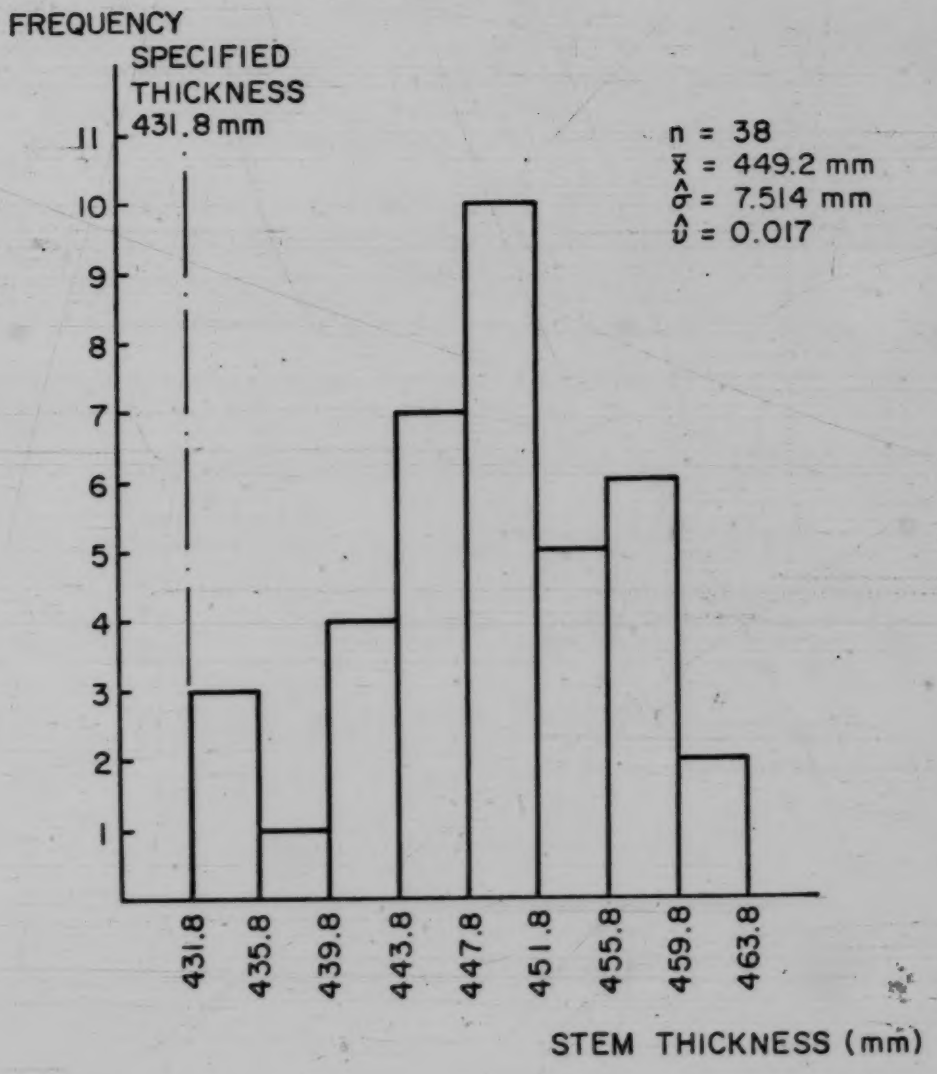


Fig. A16 Histogram of Stem Thicknesses in Zone DS

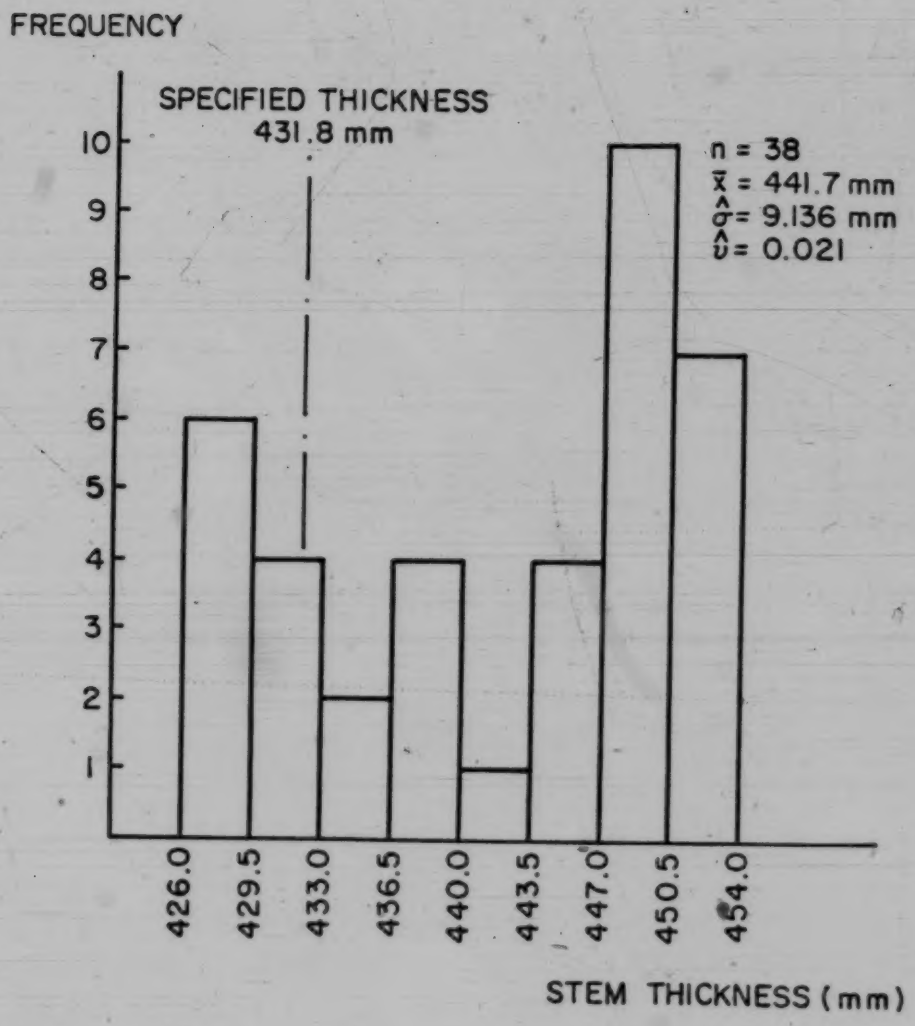


Fig. A17 Histogram of Stem Thicknesses in Zone EN

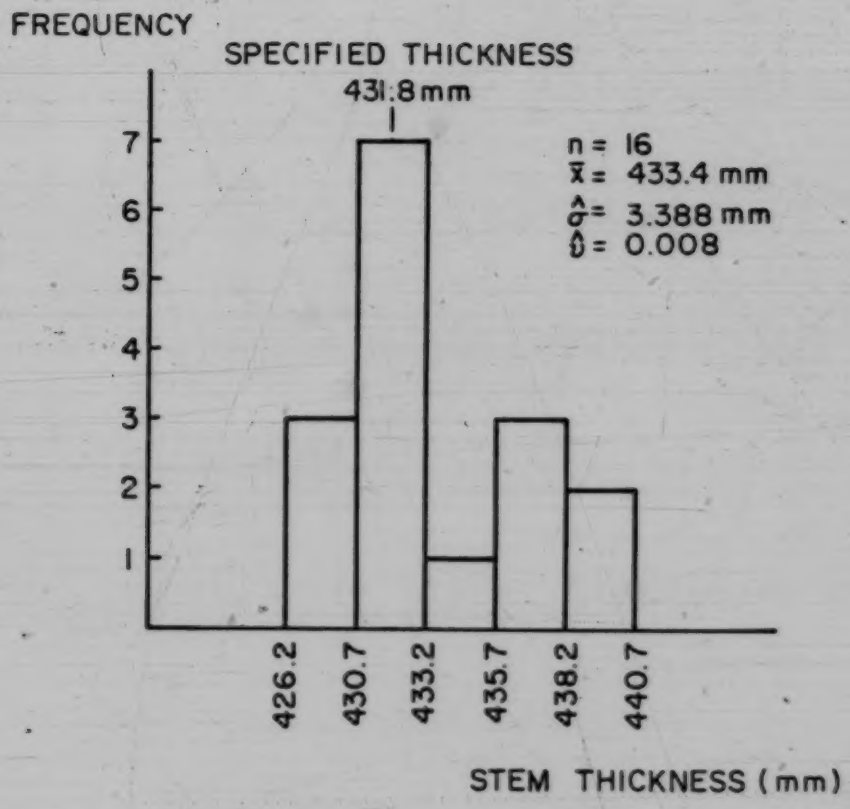


Fig. A18 Histogram of Stem Thicknesses in Zone EM

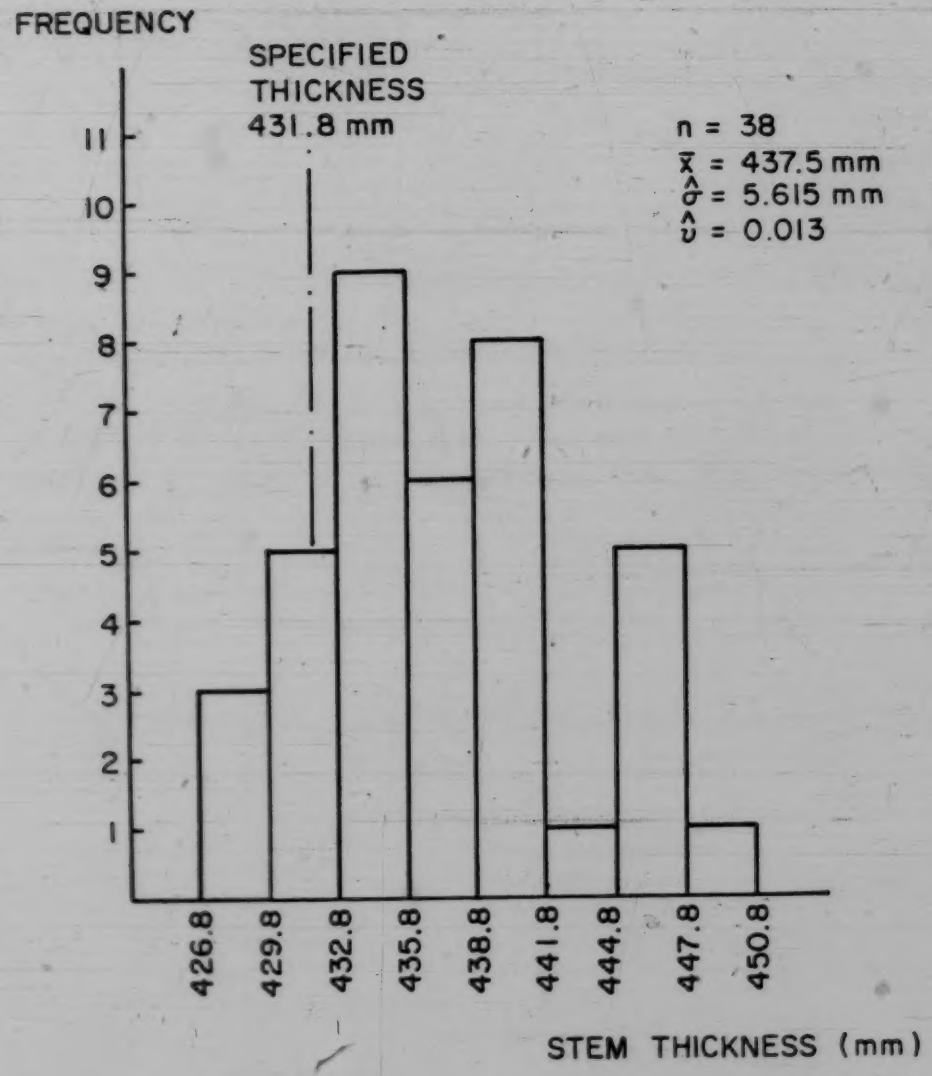


Fig. A19 Histogram of Stem Thicknesses in Zone ES

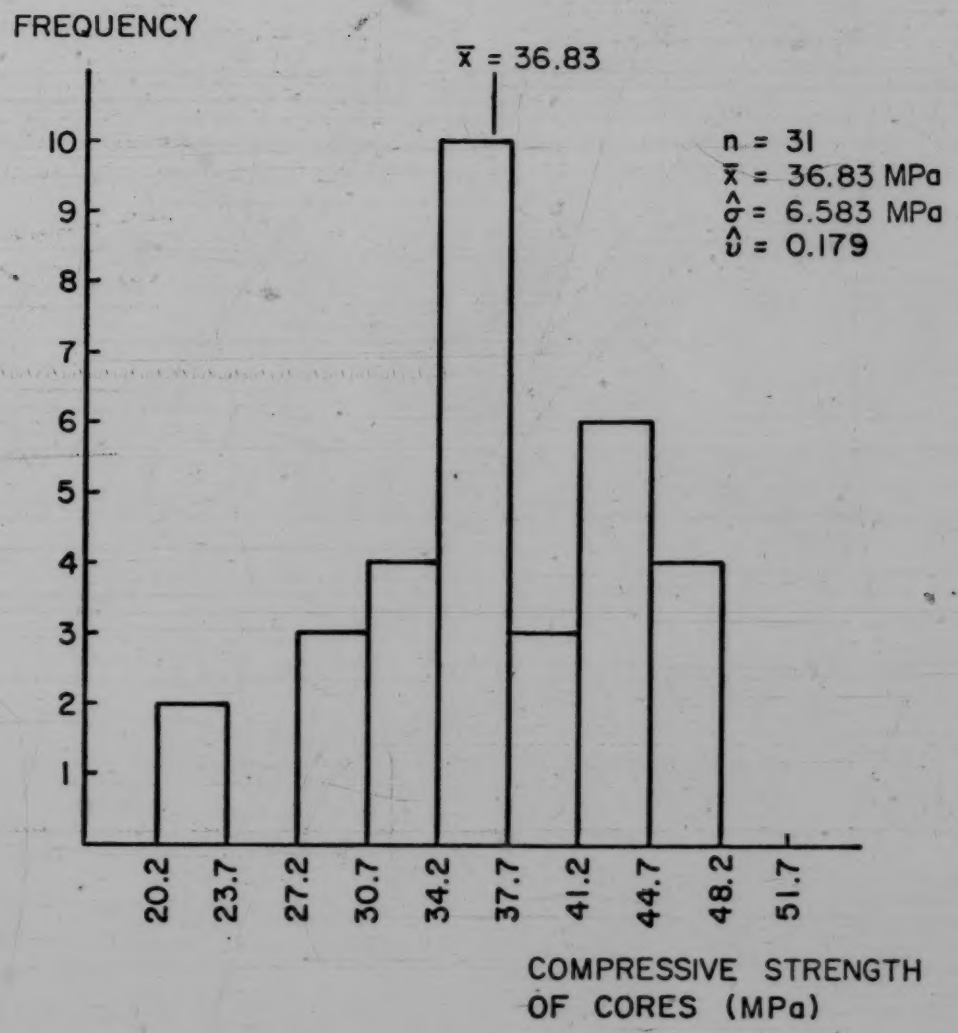


Fig. A20 Histogram of Compressive Strength of 31 Cores

$n = 38$

$\bar{x} = 3.958 \ \frac{mm}{\mu sec}$

$\hat{\sigma} = 0.194 \ \frac{mm}{\mu sec}$

$\hat{v} = 0.049$

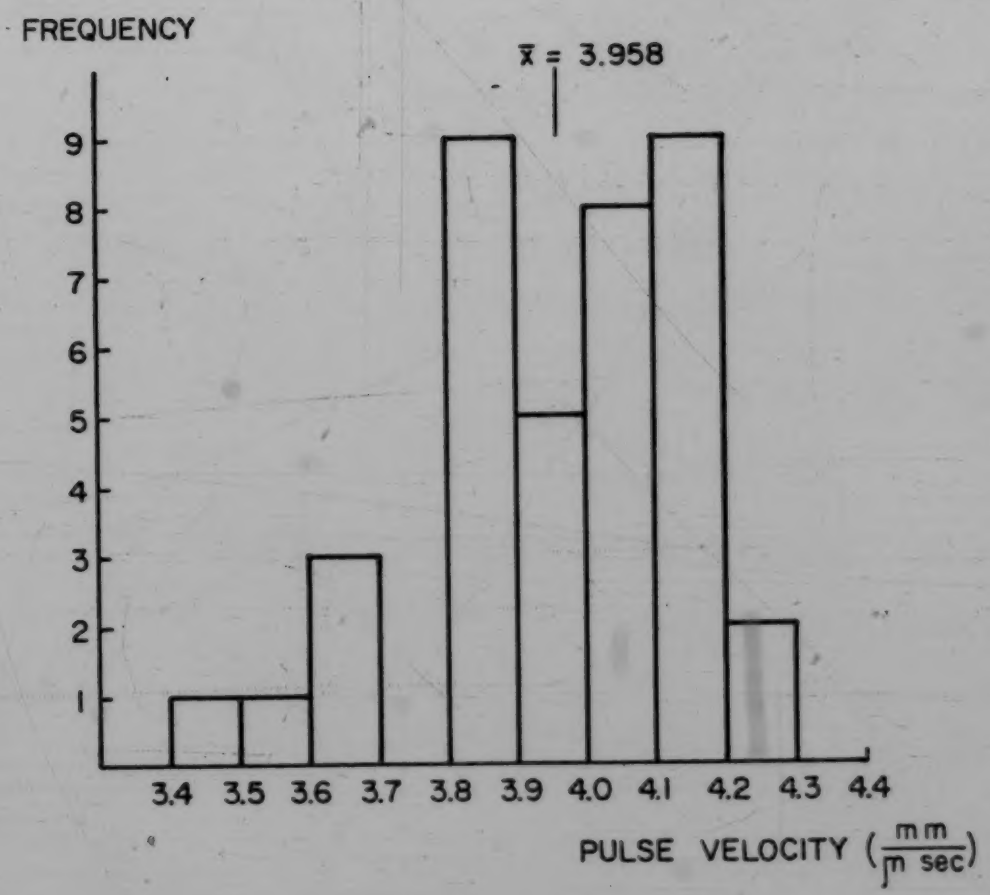


Fig. A21 Histogram of Pulse Velocities in the Girder Stem (Zone AN)

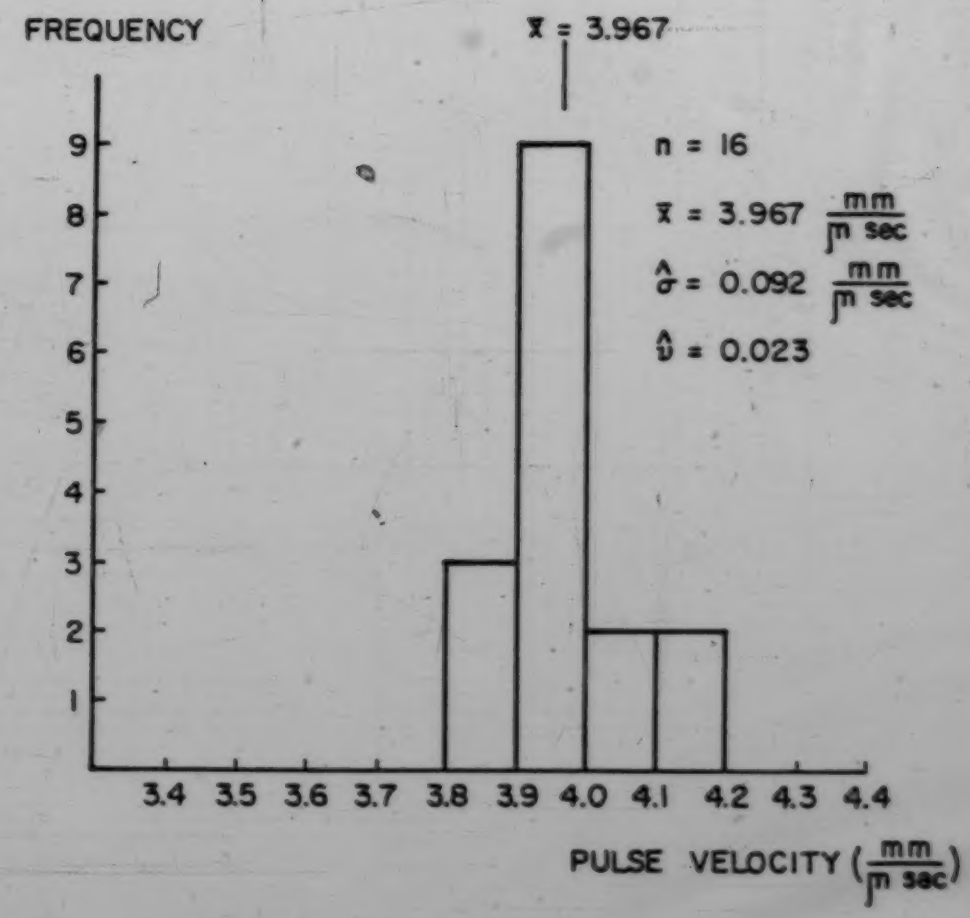


Fig. A22 Histogram of Pulse Velocities in the Girder Stem (Zone AM)

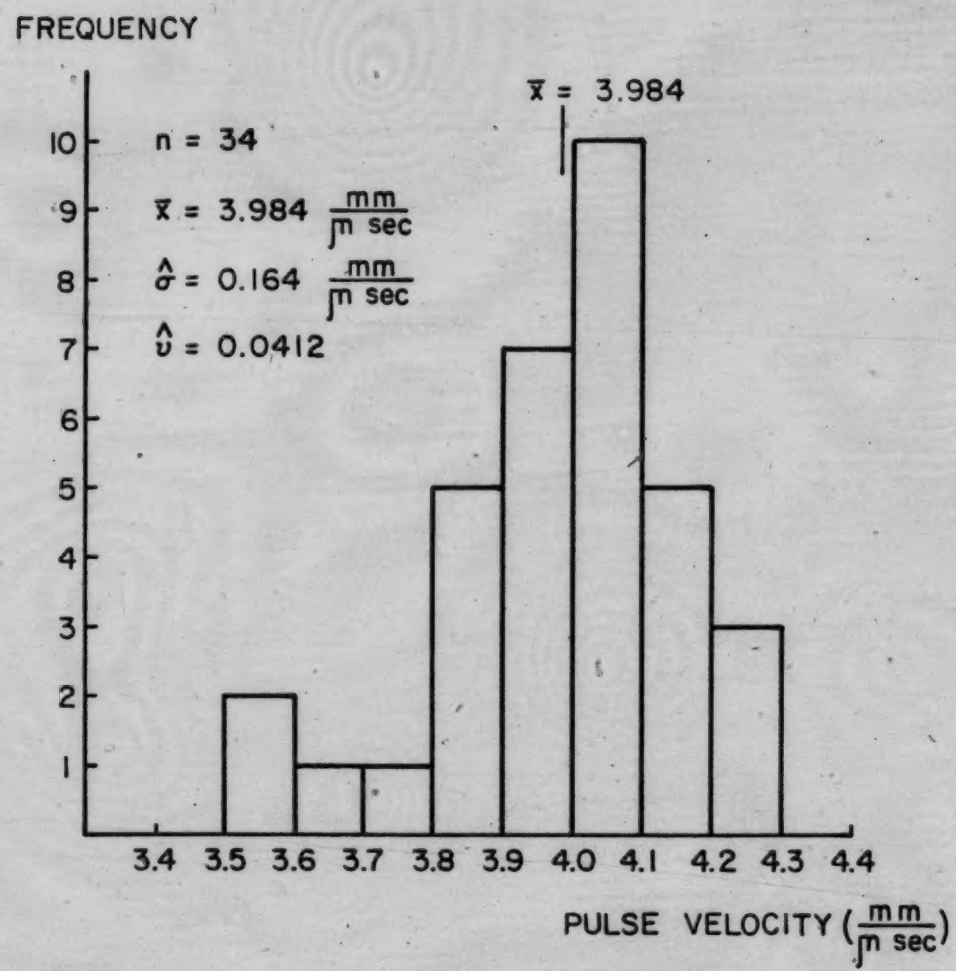


Fig. A23 Histogram of Pulse Velocity in the Girder Stem (Zone AS)

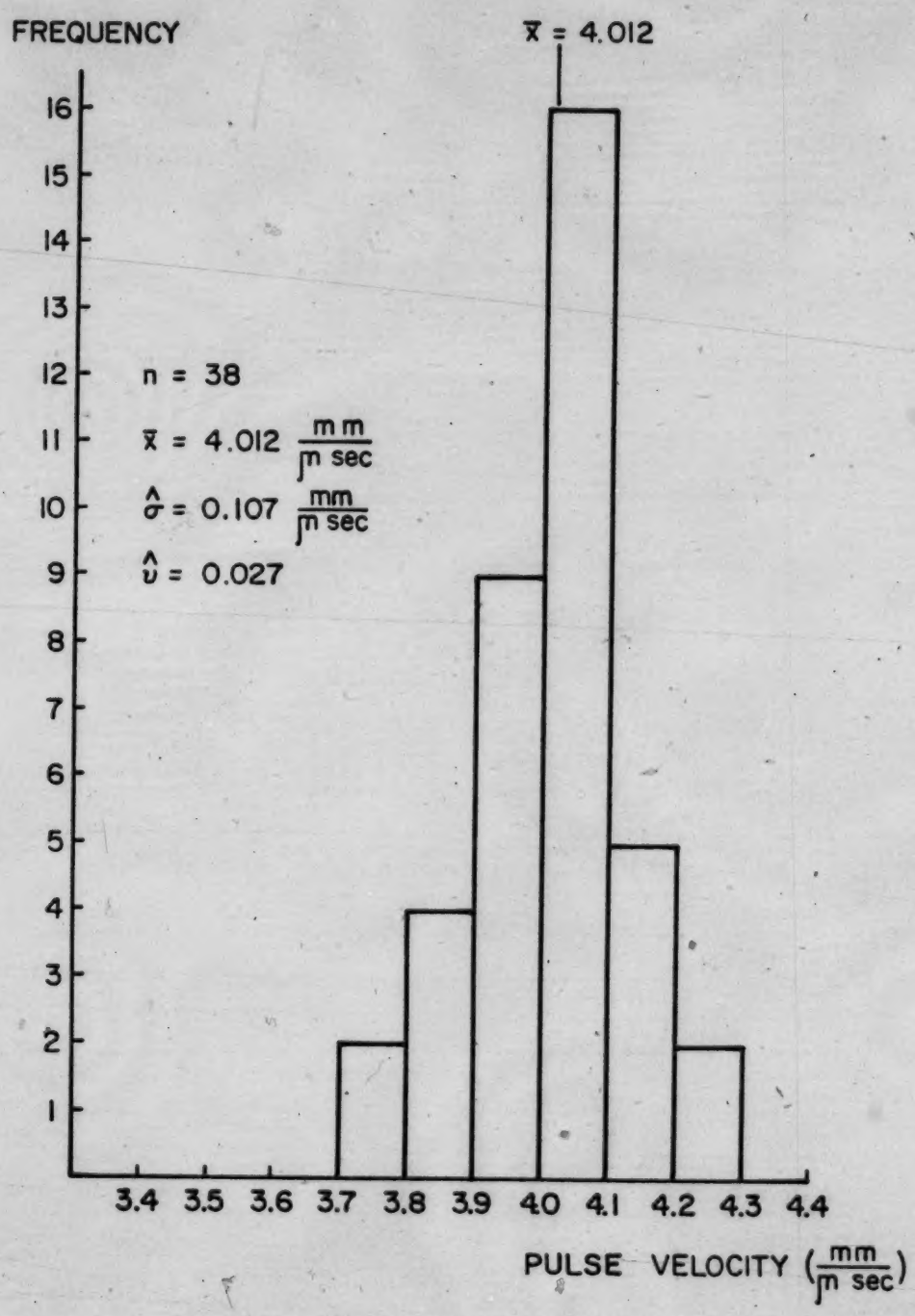


Fig. A24 Histogram of Pulse Velocities in the Girder Stem (Zone BN)

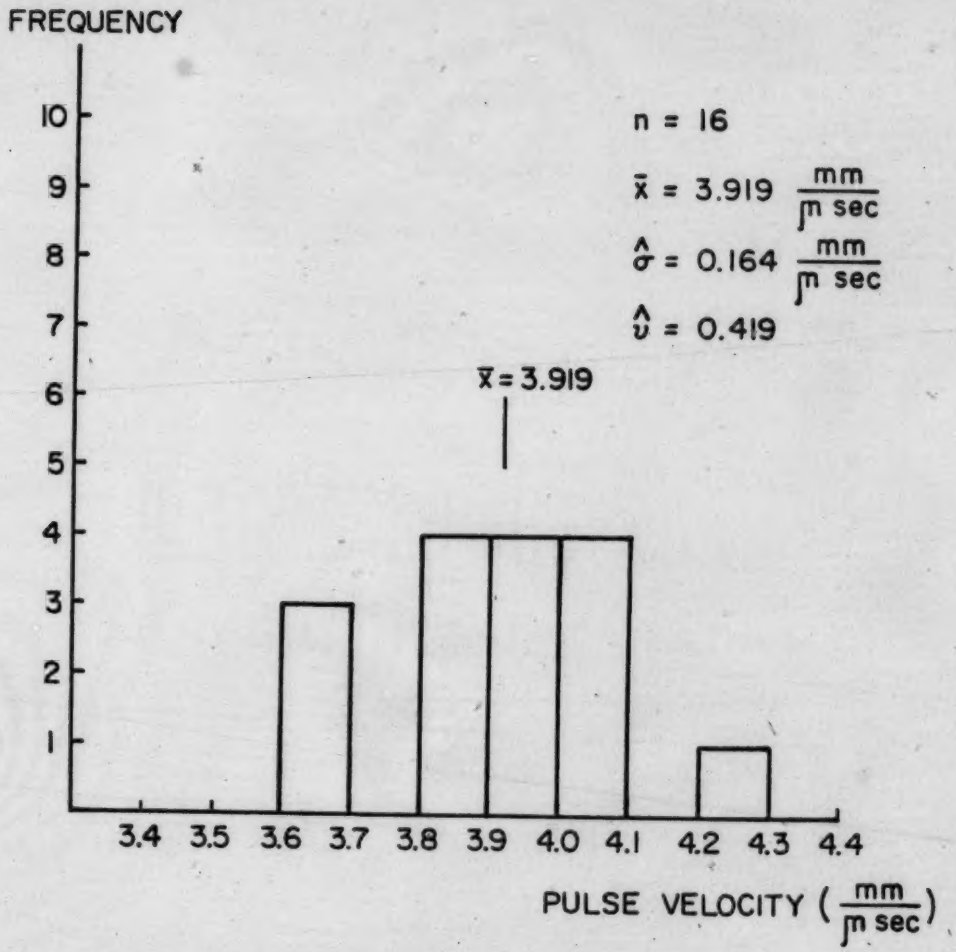


Fig. A25 Histogram of Pulse Velocities in the Girder Stem (Zone BM)

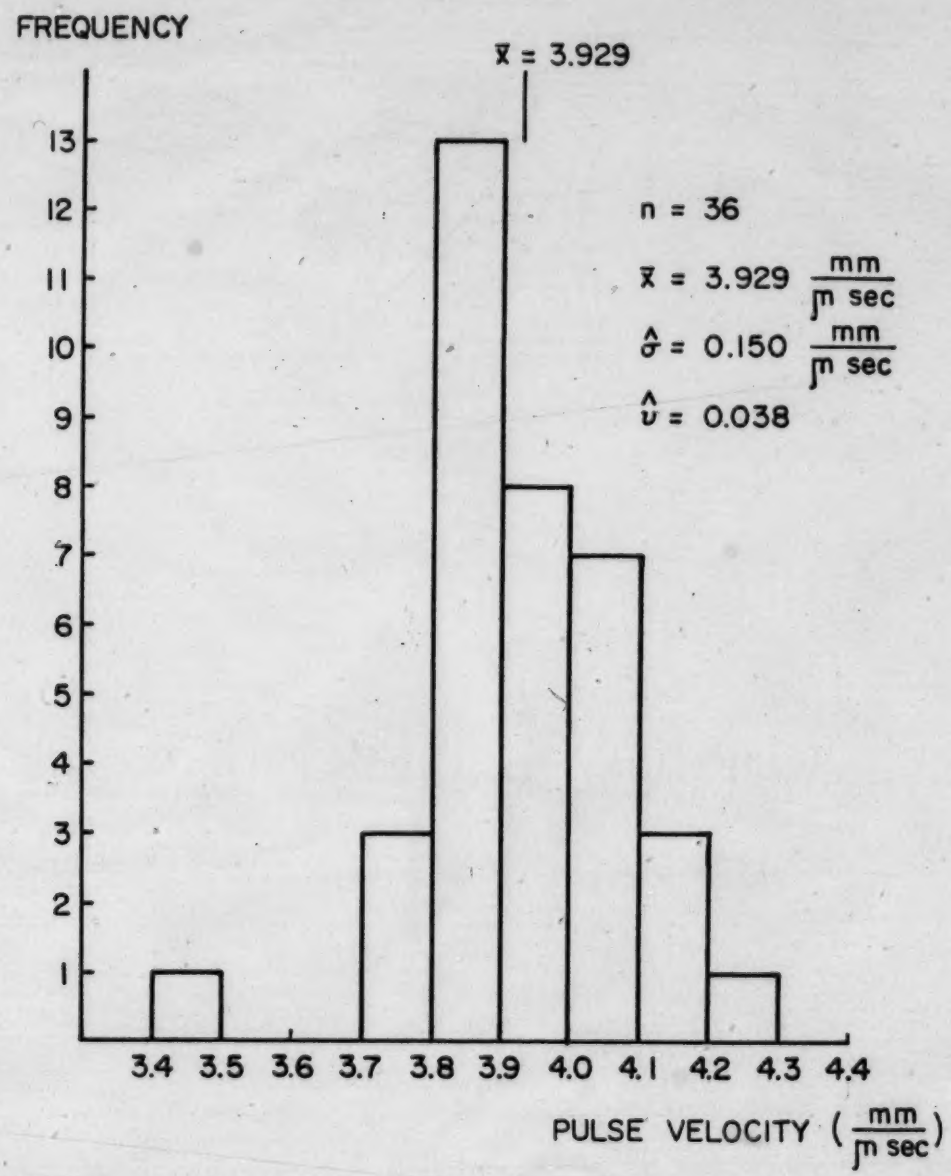


Fig. A26 Histogram of Pulse Velocities in the Girder Stem (Zone BS)

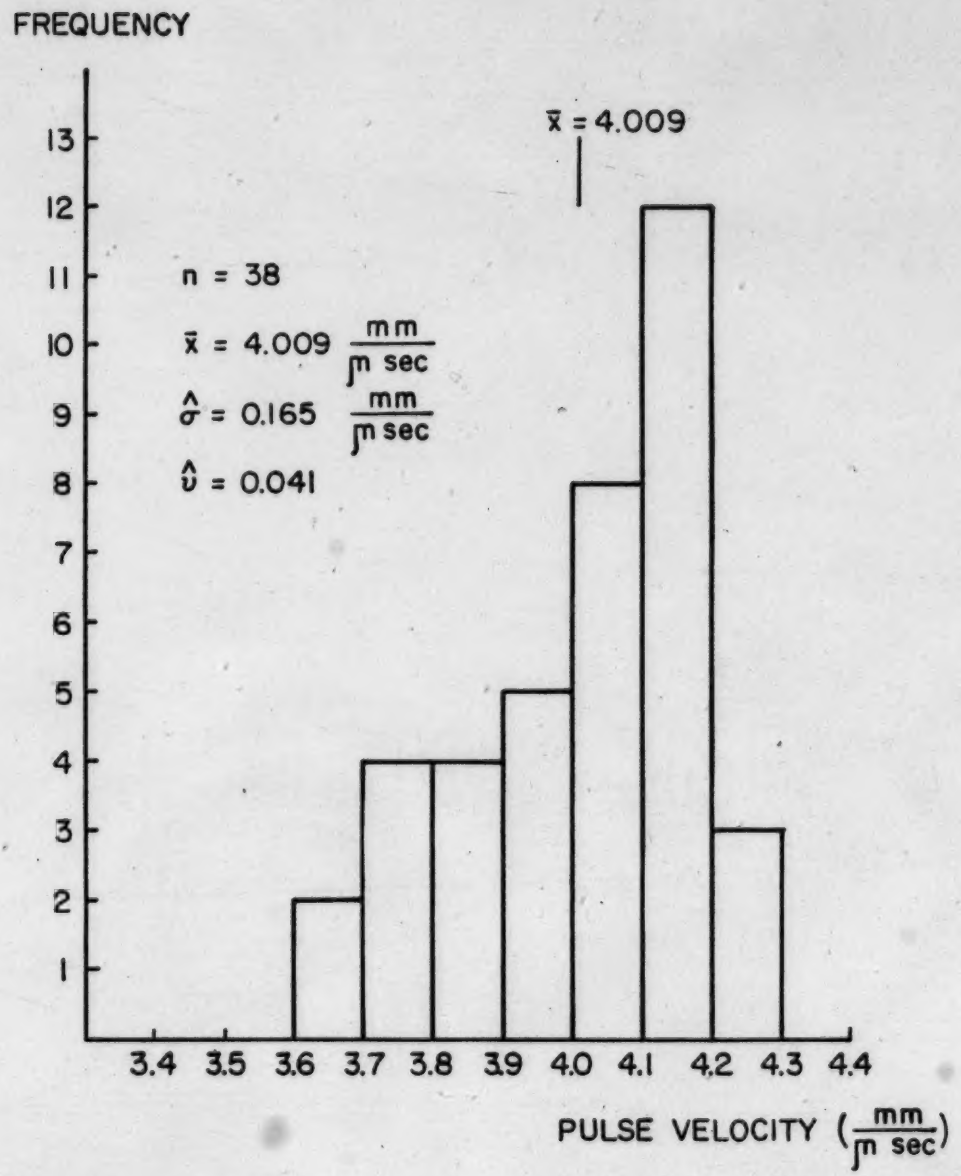


Fig. A27 Histogram of Pulse Velocities in the Girder Stem (Zone CN)

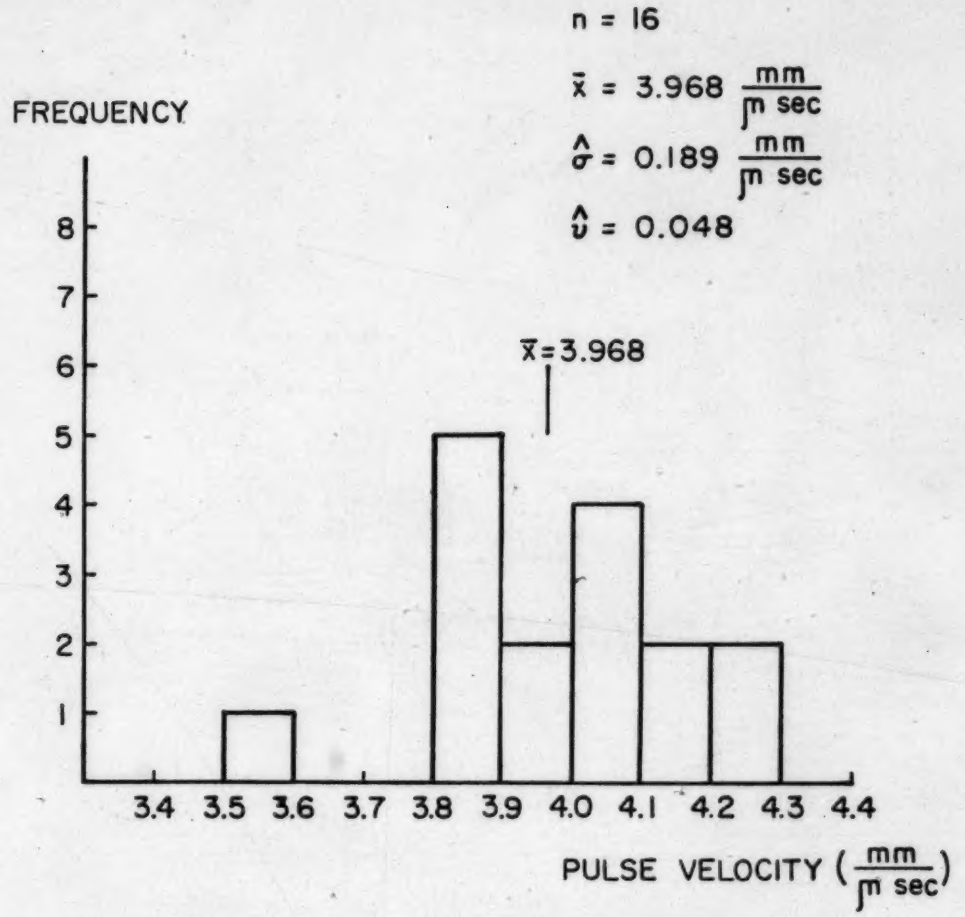


Fig. A28 Histogram of Pulse Velocities in the Girder Stem (Zone CM)

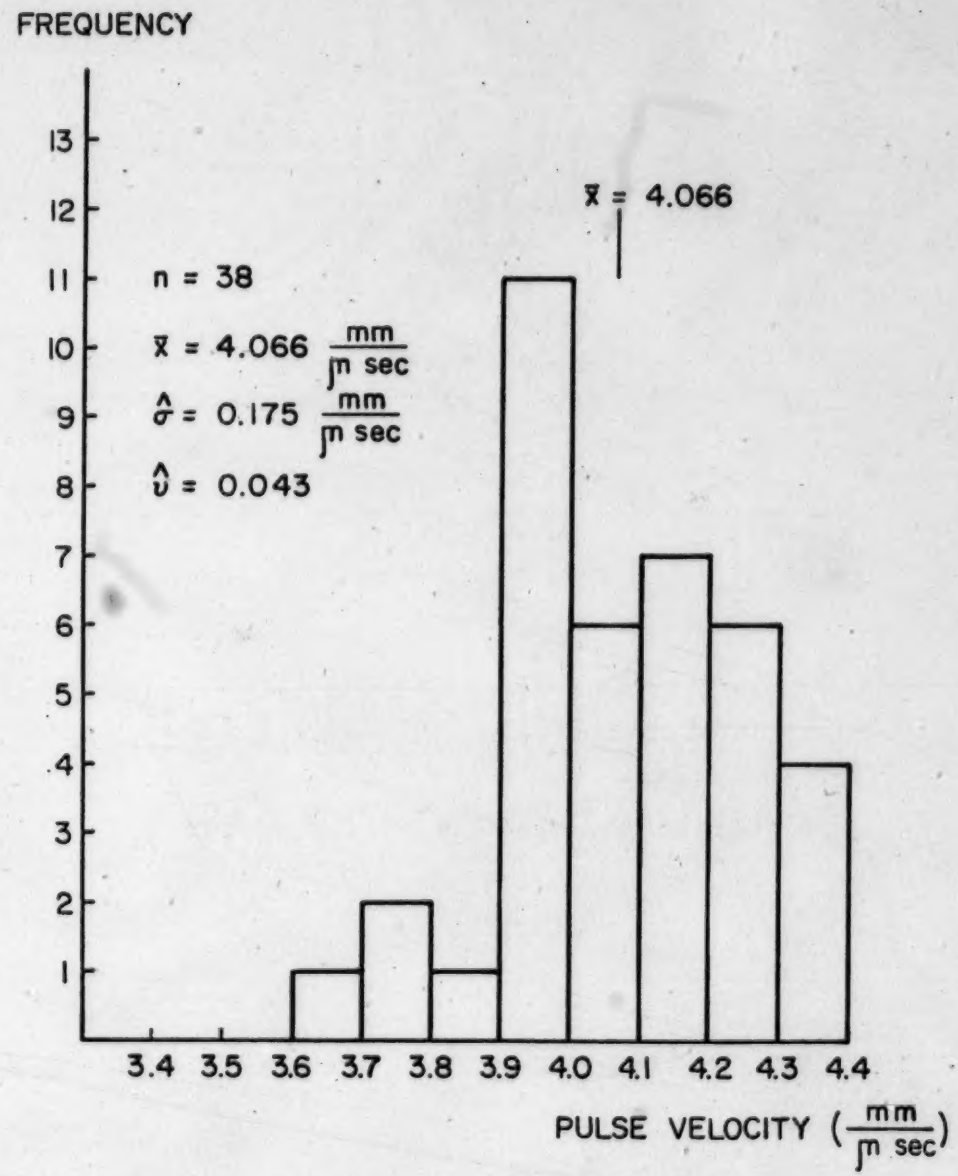


Fig. A29 Histogram of Pulse Velocities in the Girder Stem (Zone CS)

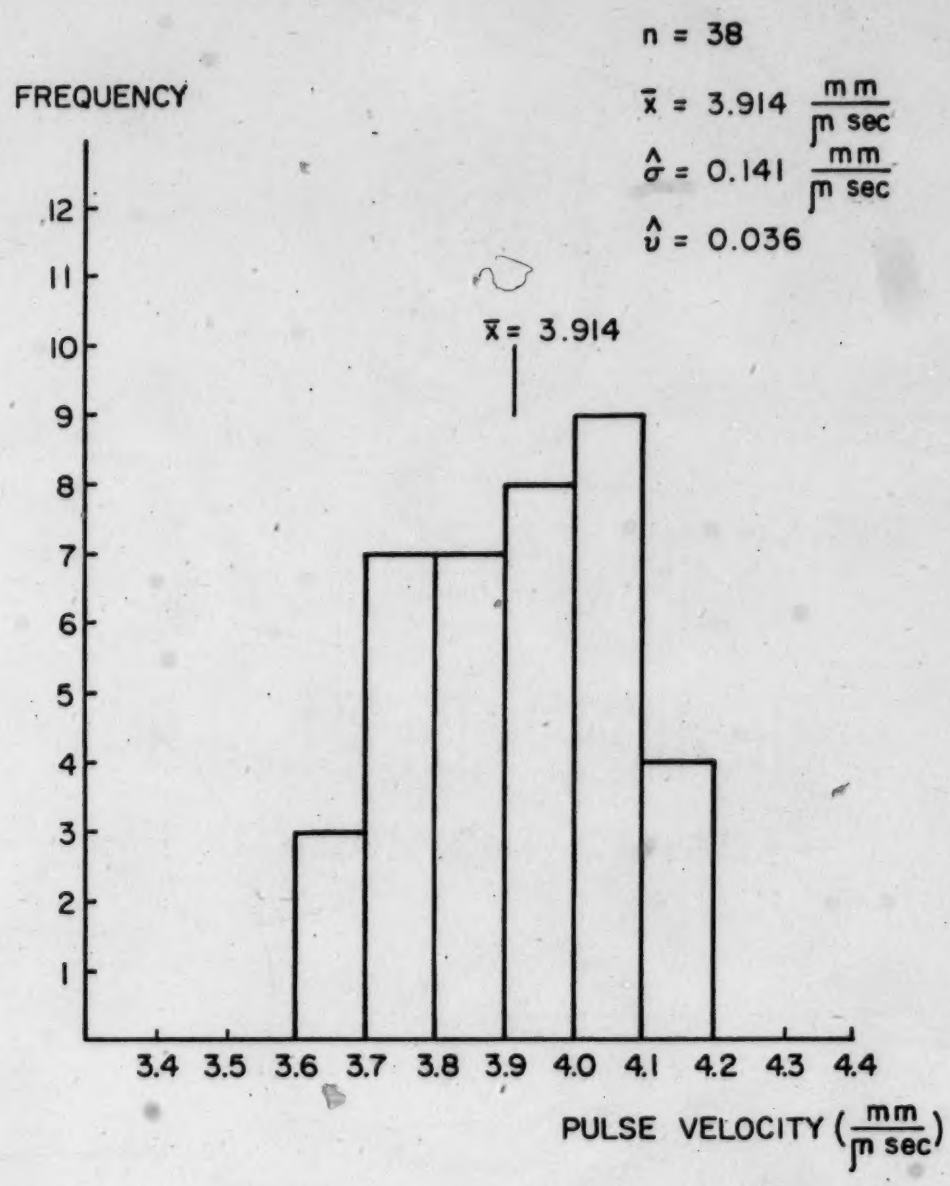


Fig. A30 Histogram of Pulse Velocities in the Girder Stem (Zone DN)

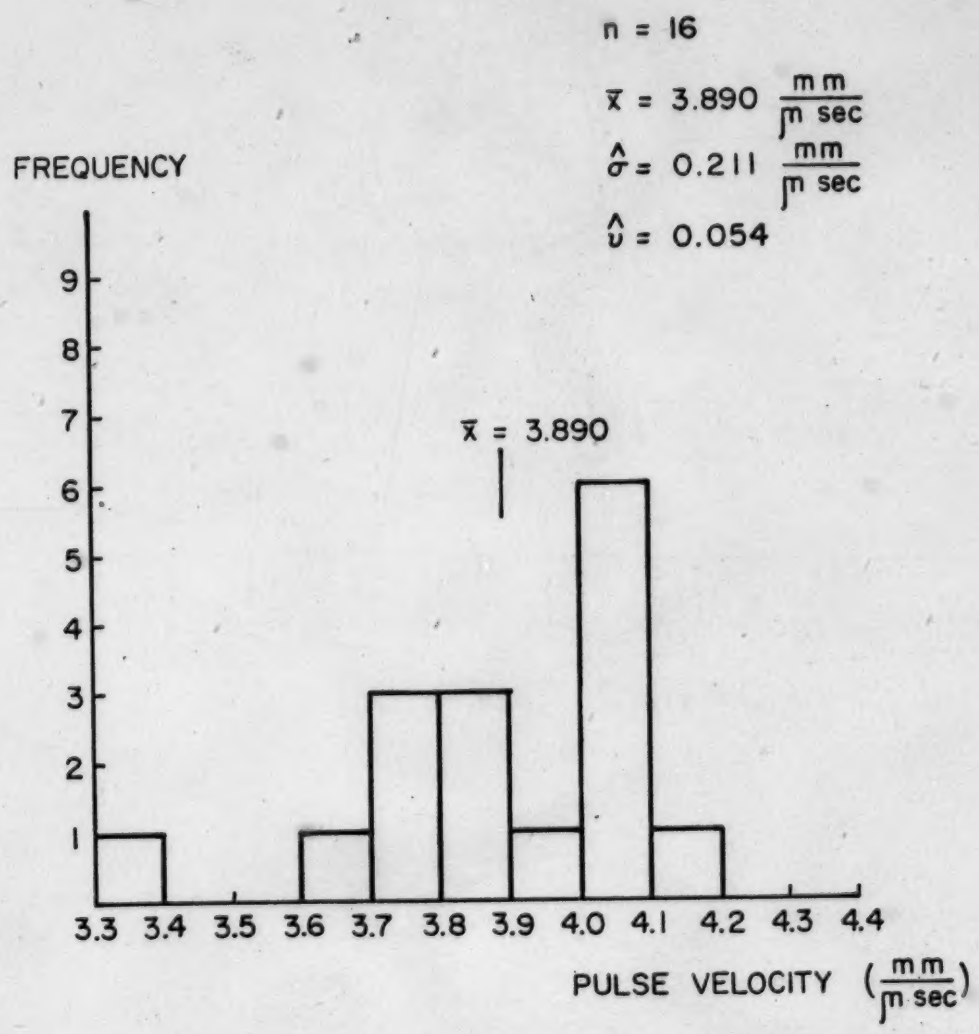


Fig. A31 Histogram of Pulse Velocities in the Girder Stem (Zone DM)

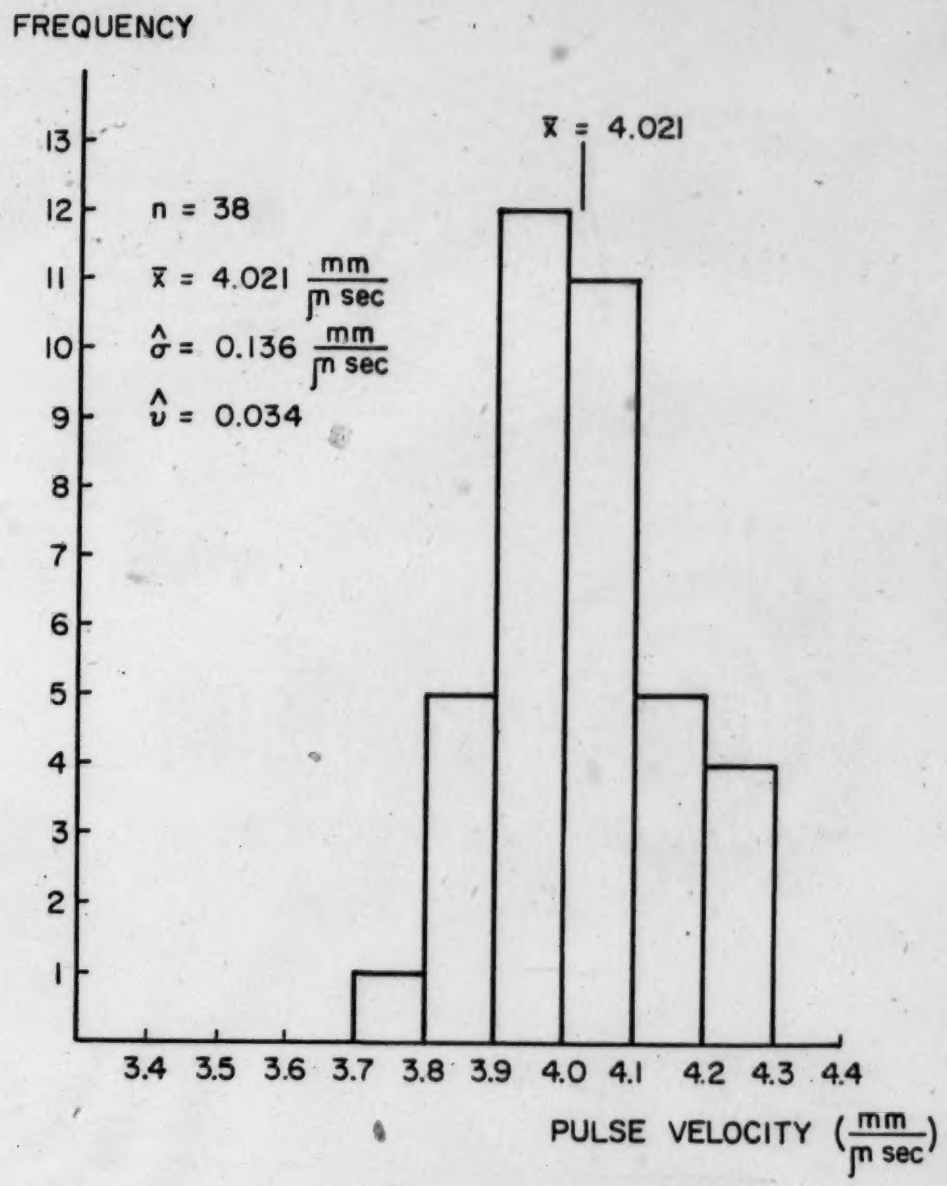


Fig. A32 Histogram of Pulse Velocities in the Girder Stem (Zone DS)

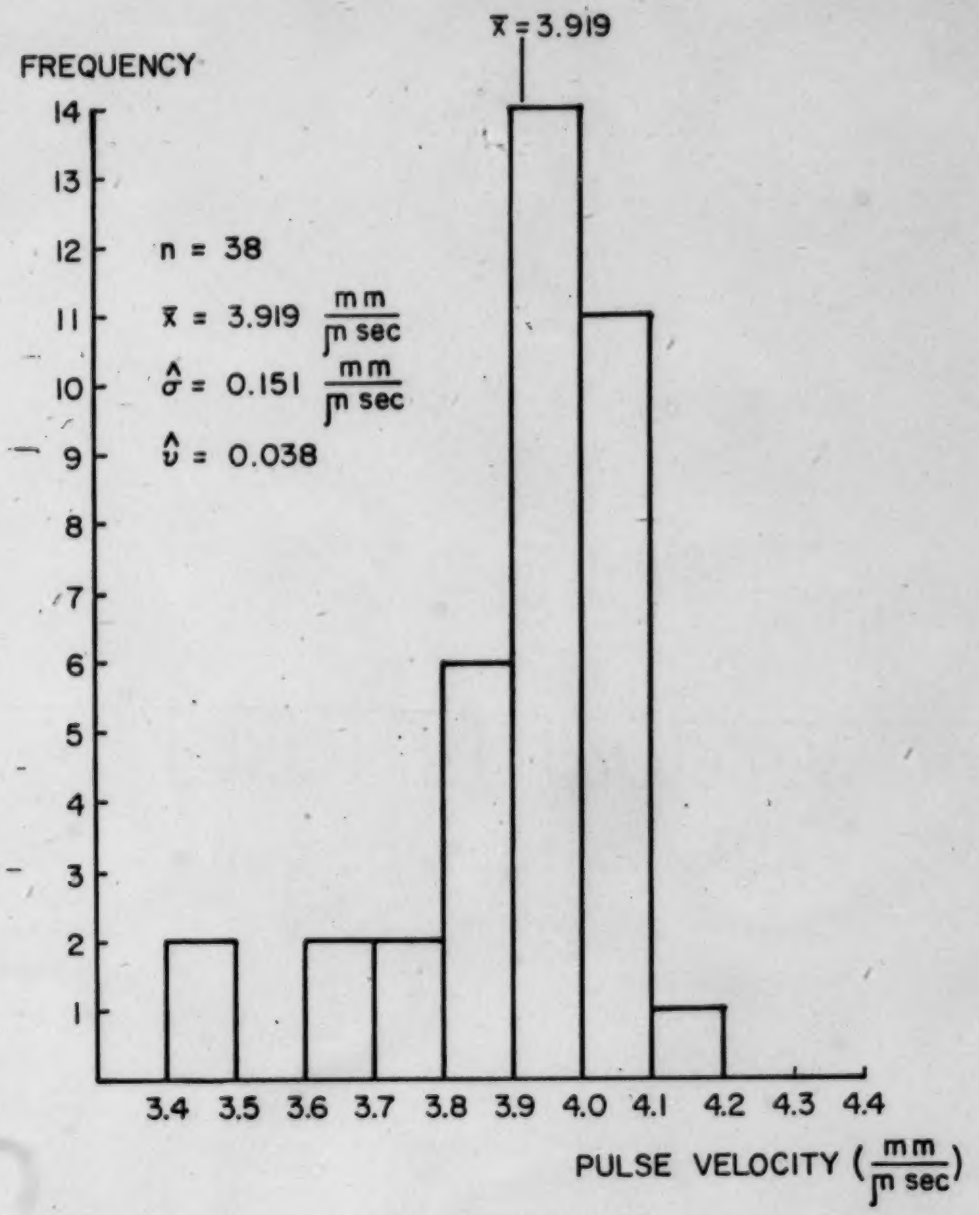


Fig. A33 Histogram of Pulse Velocities in the Girder Stem (Zone EN)

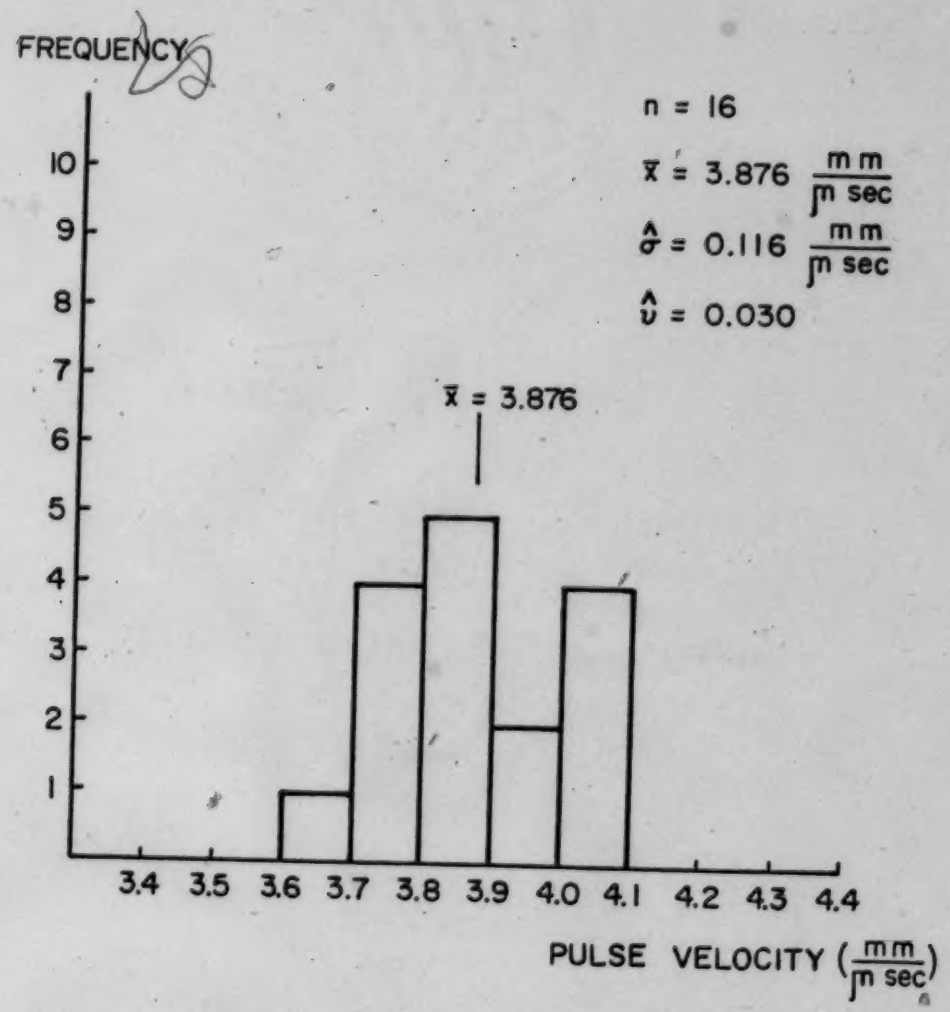


Fig. A34 Histogram of Pulse Velocities in the Girder Stem (Zone EM)

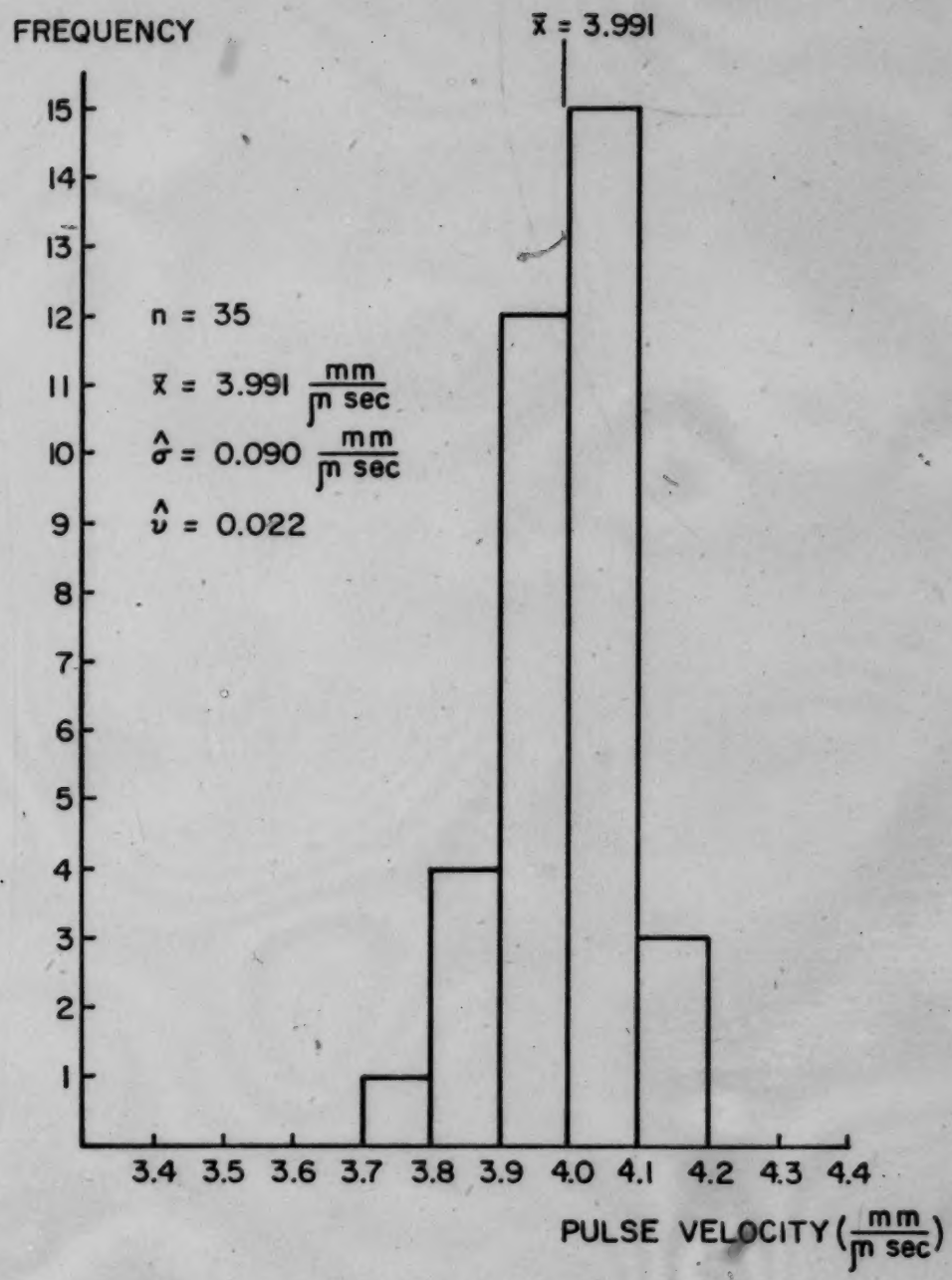


Fig. A35 Histogram of Pulse Velocities in the Girder Stem (Zone ES)

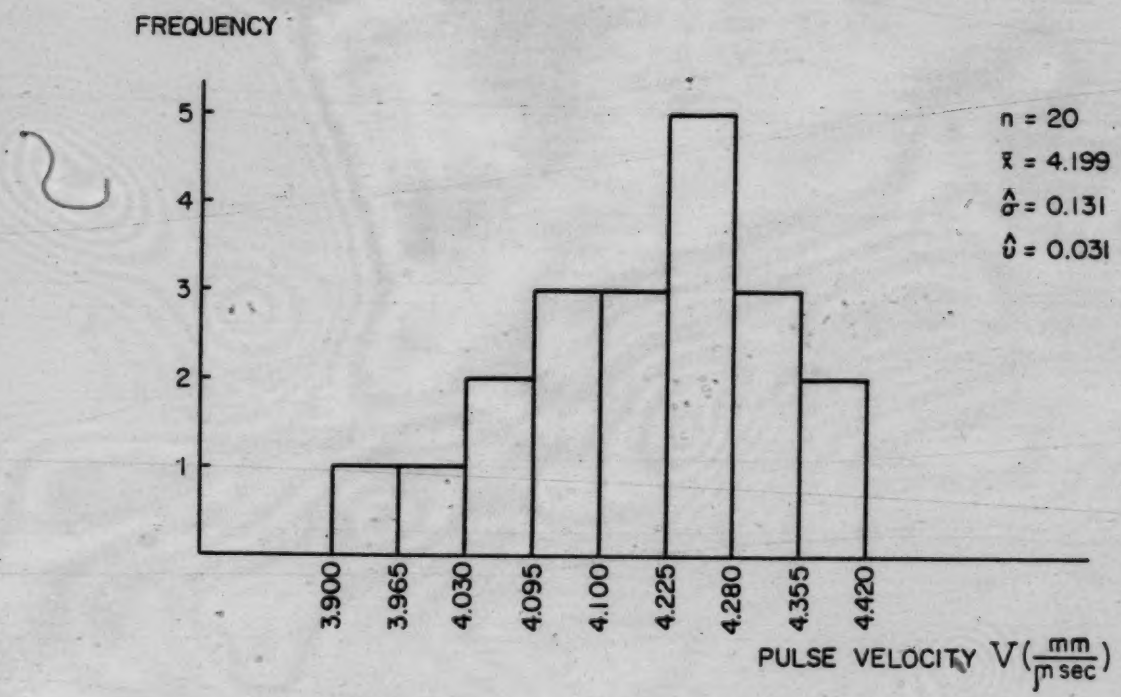


Fig. A36 Histogram of Pulse Velocities in 20 Cores

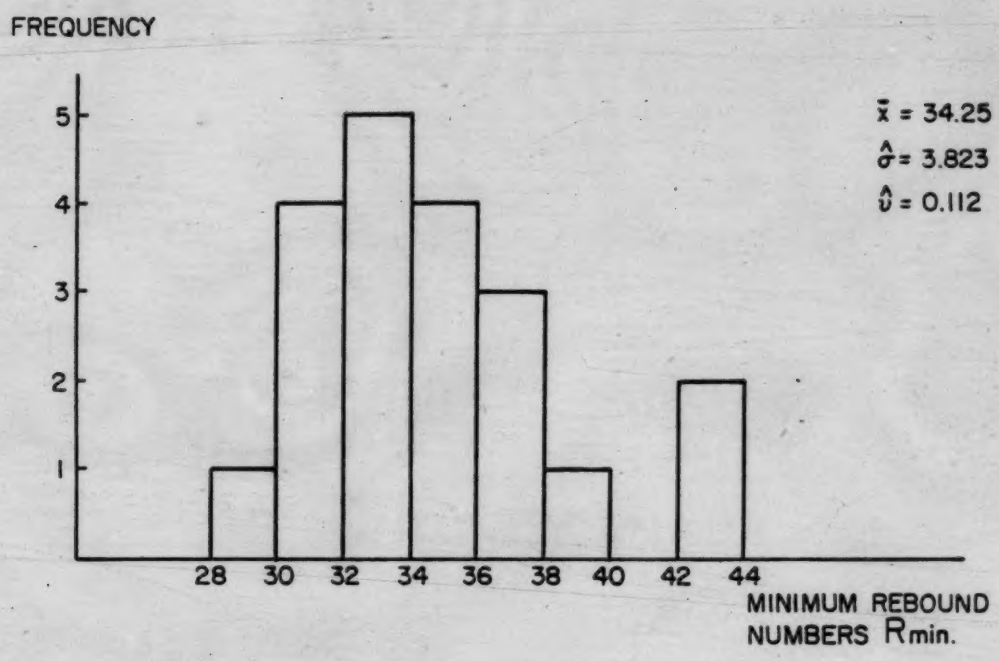


Fig. A37 Histogram of Minimum Rebound Numbers Around 20 Cores

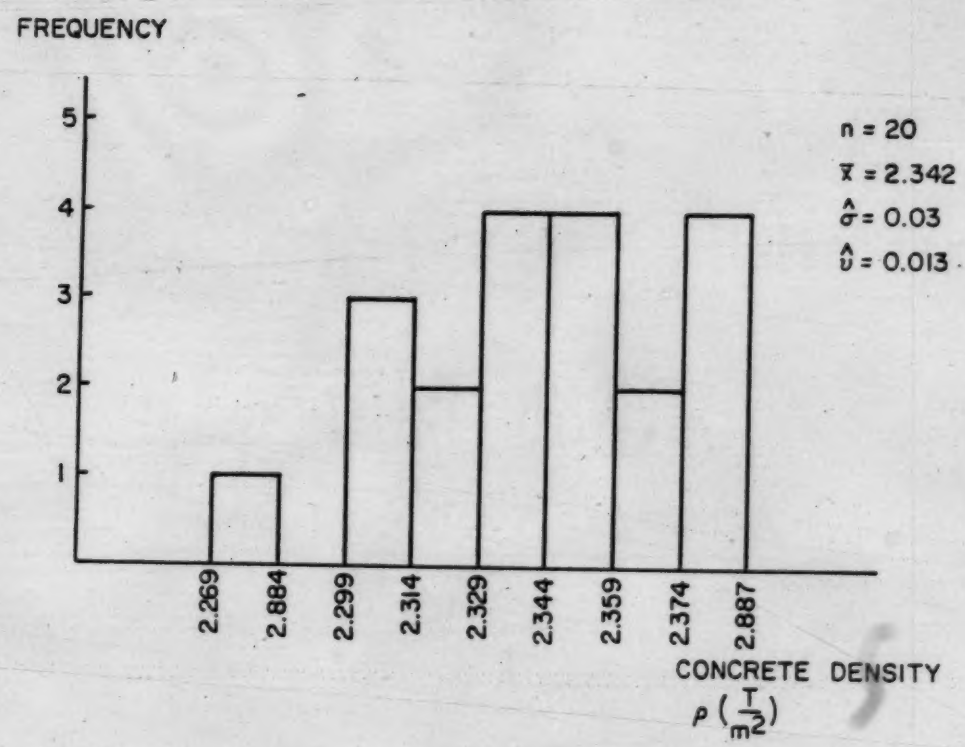


Fig. A38 Histogram of Concrete Densities of 20 Cores

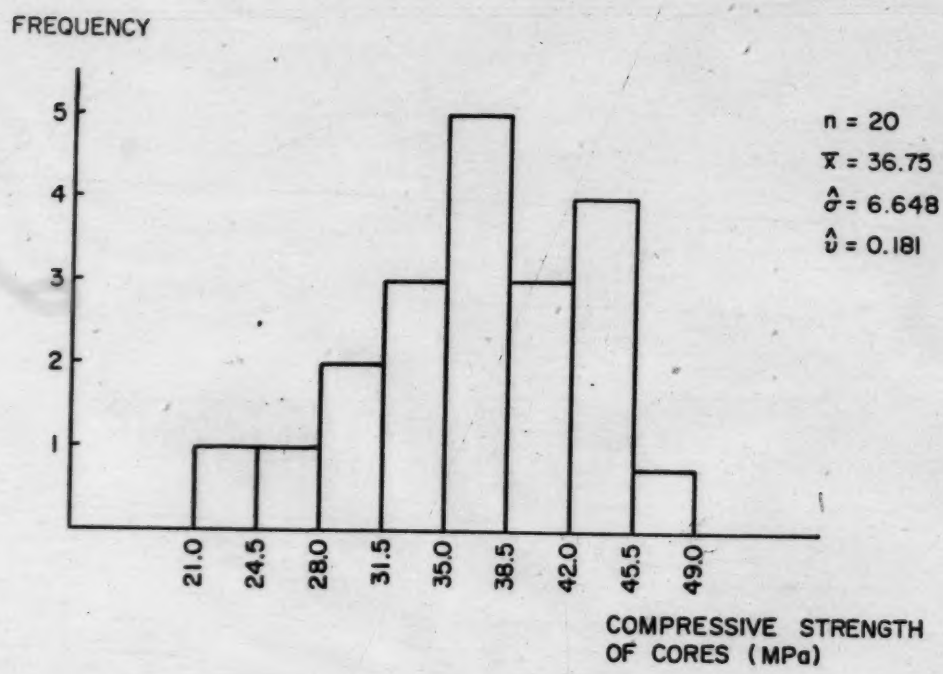


Fig. A39 Histogram of Compressive Strength of 20 Cores

APPENDIX B

EVALUATION OF PROPAGATION TIME LOSSES

Table B1 Calculation of Propagation Time Losses in Pulse Velocity Tests Due to Surface Roughness of Girder Stems

No.	Core Number	Ends Rough and Smooth: Length L_i mm	Ends Rough and Smooth: Time Reading t_i μsec	Ends Rough and Smooth: V_i mm/μsec	Both Ends Smooth: Length L_j mm	Both Ends Smooth: Time Reading t_j μsec	Both Ends Smooth: V_j mm/μsec	$\frac{L_i}{V_j}$ μsec	$\Delta t_i = t_i - \frac{L_i}{V_j}$ μsec
1	2	3	4	5	6	7	8	9	10
1	AN#23W	228.0	55.1	4.138	202.6	47.4	4.274	53.3	1.8
2	AN#23E	185.2	47.5	3.899	180.5	45.2	3.993	46.4	1.1
3	AN#29W	215.2	49.3	4.365	203.6	47.5	4.286	50.2	0.9
4	AN#29E	191.3	45.3	4.223	181.3	41.8	4.337	44.1	1.2
5	AN#32W	214.6	51.3	4.183	202.6	47.6	4.256	50.4	0.9
6	AN#32E	178.5	44.4	4.020	174.3	40.6	4.293	41.6	2.8
7	AM#9W	218.4	53.8	4.059	203.3	47.0	4.326	50.5	3.3
8	AM#9E	188.5	49.4	3.816	184.6	44.8	4.120	45.8	3.6
9	BN#4W	221.6	54.3	4.081	173.1	40.8	4.242	52.2	2.1
10	BN#4E	191.0	48.1	3.971	143.6	35.6	4.034	47.3	0.8
11	BM#8W	224.0	55.4	4.043	191.9	46.4	4.136	54.2	1.2
12	BN#8E	185.8	47.0	3.953	180.5	44.2	4.084	45.5	1.5
13	BN#31W	231.4	56.7	4.081	203.9	48.6	4.195	55.2	1.5
14	BN#31E	193.5	45.1	4.290	188.2	43.5	4.326	44.7	0.4
15	CN#1W	215.0	55.2	3.895	204.1	52.1	3.917	54.9	0.3
16	CN#1E	181.8	48.2	3.772	176.8	45.1	3.920	46.4	1.8
17	CN#5W	212.2	52.0	4.081	203.0	47.7	4.256	49.9	2.1
18	CN#5E	185.0	44.2	4.186	181.2	42.5	4.263	43.4	0.8
19	DN#3E	244.3	58.7	4.162	203.6	47.7	4.268	57.2	1.5
20	DN#3W	190.6	47.0	4.055	186.6	45.0	4.147	46.0	1.0
21	EN#8E	223.6	54.8	4.080	203.2	48.8	4.164	53.7	1.1
22	EN#8W	201.0	48.4	4.153	199.3	46.3	4.304	46.7	1.7
23	AS#5E	232.2	57.5	4.038	204.4	49.5	4.129	56.2	1.3
24	AS#8E	244.3	60.4	4.035	202.0	47.0	4.299	56.8	3.6
25	BS#3E	223.0	56.9	3.919	203.0	51.1	3.972	56.1	0.8
26	BS#7E	286.2	72.4	3.953	204.1	49.2	4.148	69.0	3.4
27	CS#1E	262.4	60.4	4.344	203.3	46.4	4.381	59.9	0.5
28	CS#5E	271.3	66.7	4.067	203.5	48.4	4.204	64.5	2.2
29	DS#4E	254.1	58.4	4.351	203.6	46.4	4.388	57.9	0.5
30	DS#31E	274.7	66.8	4.112	203.0	49.1	4.134	66.4	0.4
31	ES#29W	246.7	62.5	3.947	194.5	48.1	4.035	61.1	1.4
32	ES#23W	230.6	57.2	4.031	203.0	50.2	4.044	57.0	0.2
								Σ 45.9	

$\bar{\Delta t} = \frac{45.9}{32} = 1.434$ (μsec); $2\bar{\Delta t} = 2.868$ (μsec) $\sigma_{2\Delta t} = 1.056\sqrt{2} = 1.493$ (μsec);

$\hat{\sigma}_{\Delta t} = 1.056$ (μsec); $\Delta t = 2.868 - t_{\alpha,m}\frac{1.493}{\sqrt{32}} = 2.868 - 1.70\frac{1.493}{\sqrt{32}} = 2.42$ (μsec);

$\hat{v}_{\Delta t} = 0.736$

APPENDIX C

CONFIDENCE LIMITS

Table C1 Maximum Random Values of the Correlation Coefficient (30)

Number of Degrees of Freedom	Confidence Limit %			
	95	99	99.73	99.9
5	0.75	0.87	0.93	0.95
10	0.58	0.71	0.78	0.82
15	0.48	0.61	0.68	0.72
20	0.42	0.53	0.61	0.65
25	0.38	0.49	0.55	0.60
30	0.35	0.45	0.51	0.55
35	0.32	0.42	0.48	0.52
40	0.30	0.39	0.45	0.49
50	0.27	0.35	0.41	0.44
60	0.25	0.33	0.37	0.41
70	0.23	0.30	0.35	0.38
80	0.22	0.28	0.33	0.36
90	0.21	0.26	0.31	0.34
100	0.19	0.25	0.29	0.32
120	0.18	0.23	0.27	0.30
150	0.16	0.21	0.24	0.26
200	0.14	0.18	0.21	0.23
300	0.11	0.15	0.17	0.19
400	0.10	0.13	0.15	0.16
500	0.09	0.11	0.13	0.15
700	0.07	0.10	0.11	0.12
900	0.06	0.09	0.10	0.11
1000 and more	< 0.06	< 0.09	< 0.10	< 0.11

Table C2 Values of Student's t Distribution (30)

Number of Degrees of Freedom m	Confidence Limit (Two-Tailed Test)					
	90%	95%	98%	99%	99.8%	99.9%
1	6.31	12.7	31.82	63.7	318.3	637.0
2	2.92	4.30	6.97	9.92	22.33	31.6
3	2.35	3.18	4.54	5.84	10.22	12.9
4	2.13	2.78	3.75	4.60	7.17	8.61
5	2.01	2.57	3.37	4.03	5.89	6.86
6	1.94	2.45	3.14	3.71	5.21	5.96
7	1.89	2.36	3.00	3.50	4.79	5.40
8	1.86	2.31	2.90	3.36	4.50	5.04
9	1.83	2.26	2.82	3.25	4.30	4.78
10	1.81	2.23	2.76	3.17	4.14	4.59
11	1.80	2.20	2.72	3.11	4.03	4.44
12	1.78	2.18	2.68	3.05	3.93	4.32
13	1.77	2.16	2.65	3.01	3.85	4.22
14	1.76	2.14	2.62	2.98	3.79	4.14
15	1.75	2.13	2.60	2.95	3.73	4.07
16	1.75	2.12	2.58	2.92	3.69	4.01
17	1.74	2.11	2.57	2.90	3.65	3.96
18	1.73	2.10	2.55	2.88	3.61	3.92
19	1.73	2.09	2.54	2.86	3.58	3.88
20	1.73	2.09	2.53	2.85	3.55	3.85
21	1.72	2.08	2.52	2.83	3.53	3.82
22	1.72	2.07	2.51	2.82	3.51	3.79
23	1.71	2.07	2.50	2.81	3.49	3.77
24	1.71	2.06	2.49	2.80	3.47	3.74
25	1.71	2.06	2.49	2.79	3.45	3.72
26	1.71	2.06	2.48	2.78	3.44	3.71
27	1.71	2.05	2.47	2.77	3.42	3.69
28	1.70	2.05	2.46	2.76	3.40	3.66
29	1.70	2.05	2.46	2.76	3.40	3.66
30	1.70	2.04	2.46	2.75	3.39	3.65
40	1.68	2.02	2.42	2.70	3.31	3.55
60	1.67	2.00	2.39	2.66	3.23	3.46
120	1.66	1.98	2.36	2.62	3.17	3.37
∞	1.64	1.96	2.33	2.58	3.09	3.20
	95%	97.5%	99%	99.5%	99.9%	99.95%
	Confidence Limit (One-Tailed Test)					

APPENDIX D

CALCULATION OF STANDARD ERRORS

Table D1 Calculation of Standard Errors for 3 Calibration Curves Based on Data of 20 Cores

No.	Core Number	f'_{jc} MPa	$f_{je}^{(1)}$	$f_{je}^{(2)}$	$f_{je}^{(3)}$
1	AN#32W	43.42	37.00	39.15	39.23
2	CN#5W	32.56	33.10	36.26	36.61
3	CS#5E	38.93	35.05	35.64	35.91
4	BS#3E	29.42	35.05	27.26	37.80
5	CS#1E	45.76	43.75	50.40	48.96
6	AM#9W	43.33	35.05	40.85	40.74
7	AS#5E	41.82	44.71	38.74	39.68
8	AS#8E	37.34	38.94	42.52	42.26
9	AN#23W	38.04	30.14	34.79	35.36
10	BN#31W	33.49	36.03	35.99	36.22
11	DN#3E	35.28	34.08	37.53	37.74
12	ES#29W	27.51	33.10	28.25	28.56
13	EN#8W	38.44	32.10	38.36	37.88
14	DS#4E	44.74	37.97	46.14	45.33
15	AN#29W	44.74	40.87	43.36	43.04
16	CN#1W	21.07	33.10	24.54	24.77
17	EN#8E	41.65	37.97	35.96	36.37
18	BS#7E	32.56	36.03	34.17	34.48
19	DS#31E	35.16	34.08	32.28	32.66
20	ES#23W	29.79	37.00	30.79	31.47
	$\hat{\sigma}_t^{(4)}$		5.763	3.283	3.083

Notes: (1) $f_{je} \doteq 1.410 R_{jmin}^{0.919}$

(2) $f_{je} = 0.0045 V^{4.707} R_{min}^{0.634}$

(3) $f_{je} = -25.599 + 0.6549 R_{min} + 0.1277 V^4$

(4) $\hat{\sigma}_t = \sqrt{\frac{\Sigma (f'_{jc} - f_{je})^2}{n - 2}}$

Table D2 Calculation of Standard Errors for 69 Point Samples

Statistical Parameters \ Calibration Curves	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Size of Actual Sample n_1	20	6	8	6	20	20	20
Standard Error of Actual Sample $\hat{\sigma}_1$ (MPa)(15)	5.763(10)	4.404(11)	3.899(12)	4.157(13)	4.259(14)	3.283(10)	3.083(10)
t_{α,m_1}(1)	2.09	2.57	2.36	2.57	2.09	2.09	2.09
Standard Error of Population (MPa)(15)	7.667	7.671	6.199	7.241	5.666	4.368	4.102
t_{α,m_2}(2)	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Standard Error of 69 Point Sample $\hat{\sigma}_2$ (MPa)(16)	6.552	6.555	5.297	6.188	4.842	3.733	3.505

Notes: (1) α = 95% (confidence limit) $m_1 = n_1 - 1$

(2) α = 95% (confidence limit $m_2 = n_2 - 1 = 68$

(3) $f_c = 1.410R^{0.919}$ (Calibration on Rebound Numbers of 20 Cores)

(4) $f_c = 0.00172V^{6.957}$ (Calibration on Pulse Velocities of 6 Cores)

(5) $f_c = 0.00299V^{6.591}$ (Calibration on Pulse Velocities of 6 Simulated Groups of Cores)

(6) $f_c = 0.00203V^{5.237}R^{0.636}$ (Calibration on Pulse Velocities and Rebound Numbers of 6 Cores)

(7) $f_c = 0.020V^{5.227}$ (Calibration on Pulse Velocities of 20 Cores)

(8) $f_c = 0.0045V^{4.707}R^{0.634}$ (Calibration on Pulse Velocities and Rebound Numbers of 20 Cores)

(9) $f_c = -25.599 + 0.6549R_{min} + 0.1277V^4$ (Calibration on Pulse Velocities and Rebound Numbers of 20 Cores)

(10) From Appendix D Table D1

(11) From Table 6.4

(12) From Table 6.8

(13) From Table 6.6

(14) From Table 6.2

(15) $\sigma = \hat{\sigma}_1\left(1 + \frac{t_{\alpha,m_1}}{\sqrt{2n_1}}\right)$

(16) $\hat{\sigma}_2 = \frac{\sigma}{\left(1 + \frac{t_{\alpha,m_2}}{\sqrt{2n_2}}\right)}$ $m_2 = n_2 - 1 = 69 - 1 = 68$

APPENDIX E

SUMMARY OF IN-SITU CONCRETE STRENGTH EVALUATION

Table E1. Data of In-Situ Concrete Strength from 7 Calibration Curves

Point No.	Location	V_i mm/μsec	$1.0336 \times V_i$ mm/μsec	R_{min}	$f_e^{(1)}$ MPa	$f_e^{(2)}$ MPa	$f_e^{(3)}$ MPa	$f_e^{(4)}$ MPa	$f_e^{(5)}$ MPa	$f_e^{(6)}$ MPa	$f_e^{(7)}$ MPa
1	AN1	3.805	3.923	38	39.9	23.2	24.4	26.3	25.3	28.1	29.5
2	AN7	4.152	4.292	41	42.8	43.3	44.2	44.3	40.5	45.0	44.6
3	AN13	3.863	3.993	40	41.8	26.2	27.5	29.9	27.8	31.6	33.1
4	AN20	3.814	3.942	42	43.7	24.0	25.2	28.8	26.0	30.6	32.7
5	AN27	4.093	4.231	40	41.8	39.2	40.2	40.4	37.6	41.5	41.5
6	AN34	4.100	4.238	41	42.8	39.7	40.7	41.4	37.9	42.2	42.4
7	AM2	3.929	4.061	41	42.8	29.5	30.7	33.1	30.4	34.7	36.0
8	AM9	3.841	3.970	40	41.8	25.2	26.4	29.0	27.0	30.7	32.3
9	AM16	4.003	4.138	43	44.7	33.6	34.7	37.7	33.5	39.1	40.0
10	AS3	4.042	4.178	43	44.7	35.9	37.0	39.6	35.2	40.9	41.5
11	AS10	4.116	4.254	38	39.9	40.7	41.7	40.3	38.7	41.2	41.1
12	AS17	3.551	3.670	40	41.8	14.6	15.8	20.0	17.9	21.2	23.8
13	AS22	4.027	4.162	44	45.7	35.0	36.1	39.4	34.5	40.8	41.5
14	AS28	4.081	4.218	40	41.8	38.4	39.4	39.8	37.0	40.9	41.0
15	AS33	3.874	4.004	42	43.7	26.7	28.0	31.2	28.2	33.0	34.7
16	BN4	4.104	4.242	38	39.9	40.0	40.9	39.7	38.1	40.6	26.6
17	BN11	4.020	4.155	45	46.6	34.6	35.7	39.6	34.2	41.0	41.9
18	BN18	3.986	4.120	41	42.8	32.6	33.8	35.7	32.7	37.2	38.0
19	BN25	4.013	4.148	36	38.0	34.2	35.3	34.1	33.9	35.3	35.8
20	BN32	4.029	4.164	38	39.9	35.1	36.2	36.0	34.6	37.2	37.7
21	BN38	4.028	4.163	43	44.7	35.1	36.2	38.9	34.6	40.2	40.9
22	BM5	3.929	4.061	40	41.8	29.5	30.7	32.6	30.4	34.2	35.3
23	BM9	4.032	4.167	44	45.7	35.3	36.4	39.7	34.7	41.0	41.7
24	BM14	4.056	4.192	46	47.6	36.8	37.8	42.1	35.8	43.4	44.0
25	BS1	3.886	4.017	40	41.8	27.3	28.6	30.8	28.7	32.5	33.8
26	BS8	3.947	4.080	41	42.8	30.5	31.7	34.0	31.1	35.5	36.6
27	BS15	4.193	4.334	40	41.8	46.4	47.1	45.9	42.7	46.4	45.7
28	BS22	3.862	3.992	38	39.9	26.2	27.4	28.9	27.8	30.5	31.7
29	BS27	3.778	3.905	36	38.0	22.5	23.7	24.8	24.7	26.6	27.7
30	CN3	4.082	4.219	34	36.0	38.5	39.5	35.9	37.1	36.9	37.1
31	CN11	4.124	4.263	41	42.8	41.3	42.3	42.7	39.1	43.6	43.3
32	CN19	3.819	3.947	46	47.6	24.2	25.4	30.7	26.2	32.7	35.5
33	CN26	4.185	4.326	30	32.1	45.8	46.6	37.8	42.3	38.4	38.8
34	CM8	3.810	3.938	44	45.7	23.8	25.1	29.5	25.9	31.4	33.9

Table E1. Continued

Point No.	Location	V_i mm/μsec	1.0336xV_i mm/μsec	R_{min}	$f_e^{(1)}$ MPa	$f_e^{(2)}$ MPa	$f_e^{(3)}$ MPa	$f_e^{(4)}$ MPa	$f_e^{(5)}$ MPa	$f_e^{(6)}$ MPa	$f_e^{(7)}$ MPa
35	CM14	3.998	4.132	41	42.8	33.3	34.4	36.3	33.2	37.7	38.5
36	CS4	4.354	4.500	39	40.9	60.2	60.4	55.0	51.9	54.5	52.3
37	CS9	3.902	4.003	38	39.9	26.7	27.9	29.3	28.2	30.9	32.1
38	CS15	4.207	4.348	38	39.9	47.4	48.2	45.1	43.4	45.6	44.9
39	CS21	4.059	4.195	40	41.8	37.0	38.0	38.7	36.0	39.8	40.1
40	CS29	4.225	4.367	39	40.9	48.9	49.6	47.0	44.4	47.3	46.4
41	CS35	3.970	4.103	46	47.6	31.7	32.9	37.6	32.0	39.2	40.7
42	CS37	3.682	3.805	34	36.0	18.8	20.0	20.9	21.6	22.7	23.4
43	DN1	3.894	4.025	38	39.9	27.7	29.0	30.1	29.0	31.7	32.8
44	DN6	3.899	4.030	40	41.8	28.0	29.2	31.3	29.2	33.0	34.3
45	DN13	3.734	3.859	41	42.8	20.7	21.9	25.4	23.3	27.3	29.6
46	DN17	3.672	3.795	49	50.4	18.4	19.6	26.0	21.3	28.3	33.0
47	DN22	3.775	3.902	41	42.8	22.3	23.6	26.9	24.6	28.8	30.9
48	DN32	4.162	4.302	36	38.0	44.0	44.9	41.3	41.0	41.9	41.7
49	DN33	4.096	4.234	30	32.1	39.4	40.4	33.8	37.8	34.7	35.1
50	DM3	4.035	4.171	43	44.7	35.5	36.6	39.3	34.9	40.6	41.2
51	DM10	3.302	3.413	40	41.8	8.8	9.8	13.1	12.2	15.1	17.9
52	DM16	3.702	3.826	40	41.8	19.5	20.7	23.9	22.2	25.8	28.0
53	DS7	4.057	4.193	36	38.0	36.8	37.9	36.1	35.9	37.2	37.4
54	DS14	3.872	4.002	38	39.9	26.6	27.9	29.2	28.1	30.9	32.0
55	DS21	4.044	4.180	47	48.5	36.1	37.1	42.0	35.3	43.4	44.2
56	DS30	4.291	4.435	48	49.5	54.4	54.9	58.1	48.1	58.1	55.2
57	EN6	4.011	4.146	42	43.7	34.1	35.2	37.5	33.8	38.9	39.6
58	EN12	3.907	4.038	38	39.9	28.4	29.6	30.6	29.5	32.2	33.2
59	EN18	3.444	3.560	38	39.9	11.8	12.9	15.8	15.2	17.8	19.8
60	EN28	3.930	4.062	41	42.8	29.5	30.8	33.2	30.4	34.8	36.0
61	EN35	3.890	4.021	41	43.7	27.5	28.8	31.9	28.8	33.6	35.3
62	EM4	3.768	3.895	40	41.8	22.1	23.3	26.2	24.4	28.1	30.0
63	EM11	3.811	3.939	40	41.8	23.9	25.1	27.8	25.9	29.6	31.3
64	EM15	4.011	4.146	41	42.8	34.1	35.2	36.9	33.8	38.3	39.0
65	ES3	3.795	3.923	37	38.9	23.2	24.4	25.9	25.3	27.6	28.9
66	ES10	4.017	4.152	48	49.5	34.4	35.5	41.1	34.1	42.6	43.8
67	ES17	3.976	4.110	40	41.8	32.1	33.2	34.7	32.3	36.2	37.0
68	ES24	4.059	4.195	46	47.6	37.0	38.0	42.2	36.0	43.5	44.1
69	ES34	4.169	4.309	38	39.9	44.6	45.4	43.1	41.4	43.7	43.3

Table E1. Continued

Point / Location No.	V_i mm/μsec	1.0336xV_i mm/μsec	R_{min}	$f_e^{(1)}$ MPa	$f_e^{(2)}$ MPa	$f_e^{(3)}$ MPa	$f_e^{(4)}$ MPa	$f_e^{(5)}$ MPa	$f_e^{(6)}$ MPa	$f_e^{(7)}$ MPa
Mean $\bar{x}$		4.087		42.2	32.2	33.3	34.7	32.1	36.1	36.7
Standard Deviation $\hat{\sigma}_e$		0.192		3.545	9.567	9.397	8.083	7.326	7.658	6.876
Coef. of Variation $\hat{v}_e$		0.047		0.084	0.297	0.283	0.233	0.228	0.212	0.187
Standard Error (from Table D2 $\hat{\sigma}_t$ (MPa)				6.552	6.555	5.297	6.188	4.842	3.733	3.505
Total Sample Standard Deviation $\hat{\sigma}$ (8) (MPa)				7.450	11.597	10.787	10.180	8.782	8.519	7.717
Total Sample Coefficient of Variation $\hat{v}$ (9)				0.177	0.360	0.324	0.293	0.274	0.234	0.210
Coefficient of Variation of Population v" (10)				0.207	0.421	0.379	0.343	0.321	0.274	0.246
Population Mean μ'				40.4	29.4	30.7	32.2	30.0	34.0	34.8

Notes: (1) $f_e = 1.410R^{0.919}$ (Calibration on Rebound Numbers of 20 Cores)

(2) $f_e = 0.00172V^{6.957}$ (Calibration on Pulse Velocities of 6 Cores)

(3) $f_e = 0.00299V^{6.591}$ (Calibration on Pulse Velocities of 6 Simulated Groups of Cores)

(4) $f_e = 0.00203V^{5.237}R^{0.6358}$ (Calibration on Pulse Velocities and Rebound Numbers of 6 Cores)

(5) $f_e = 0.020V^{5.227}$ (Calibration on Pulse Velocities of 20 Cores)

(6) $f_e = 0.0045V^{4.707}R^{0.635}$ (Calibration on Pulse Velocities and Rebound Numbers of 20 Cores)

(7) $f_e = -25.599 + 0.6549R_{min} + 0.1277V^4$ (Calibration on Pulse Velocities and Rebound Numbers of 20 Cores)

(8) $\hat{\sigma} = \sqrt{\hat{\sigma}_e^2 + \hat{\sigma}_t^2}$

(9) $\hat{v} = \frac{\hat{\sigma}}{\bar{x}}$

(10) $v'' = \hat{v} + t_{\alpha,m}\frac{\hat{v}}{\sqrt{2n}}$; $t_{\alpha,m} = 2.0$; $m = n - 1 = 68$; $\alpha = 95\%$ confidence limit